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What is Truth? Lived Experiences of Science Education: explorations of real and virtual laboratories in Further Education

Neil Francis Peirson

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ABSTRACT

Virtual laboratories (VLs) are widely used in teaching practical science. Studies in higher education have suggested that VLs provide similar learning outcomes to real laboratories, with enhanced learning when they are both used. However, little is known of students learning experiences, particularly in Further Education (FE).

This small-scale practitioner research project explores the lived experience of FE science students and teachers, through surveys and thematic analysis of semi-structured interviews. Questions focused on the reality of the experience in VLs, and the trust students have in the results of both laboratories. The value of VLs as teaching tools is also examined.

Responses suggest that students trust the results of both the VL and the real laboratory. However, their experiences – Presence, Interaction, Motivation, Control and Consequence – are richer in the real laboratory. The trust that students and teachers have in the both the real and VL appears to derive from two sources. Trust in external authority: governments, universities, institutions, corporations, textbooks, syllabuses, and experts which define an "objective truth". This is transferred through the education system – through teachers – forming the basis of trust in the VL. Trust in the real laboratory comes from empirical evidence: students believe '*because they saw it happen with their own eyes'*; although they do not always trust their own abilities. This research provides tentative evidence that students who show greater trust in the VL perform better in their exams.

Students feel VLs show *'the theory behind an experiment'* and allow them to practice skills, through multiple repetitions with instant feedback. They could be considered as embodiments of thought experiments, which able learners to change their concepts. However, VLs do not provide the interactions – developing social, manipulative, and spatial skills – found in the real laboratory. Additionally, practical science shows the characteristics of a signature pedagogy; however, VLs do not seem to meet all the criteria. VLs provide a valuable teaching tool, 'but can never be a full replacement'.

Key words: Virtual Laboratory, Practical Science, Further Education, Truth

TABLE OF CONTENTS

TABLE OF FIGURES

TABLE OF TABLES

CHAPTER 1

INTRODUCTION

There is an 'absence of descriptive and qualitative research exploring everyday educational practices using virtual laboratories in naturalistic contexts'

(Sellberg, Nazari and Solberg, 2024).

Introduction

'What is truth?' (St. John, 18:38) has been a contentious issue for well over two thousand years. This work attempts to use practical science to say something about truth and reality. Science is a way of discovering about the world, it gives us a set of strategies and norms. However, the boundaries of science – as opposed to other forms of knowledge – are pliable and definitions are disputed (Bird, 1998; Okasha, 2016; O'Hear, 1990; Putnam, 1981; Redman, 1993). Within science there is a drive towards deductive logic, however many of the laws of science are based on inductive logic. Practical science provides a way to investigate reality, though experimentation, observation and measurement. Virtual science laboratories use computer models to simulate real laboratory experiments. By exploring the experiences of students working in both real and virtual laboratories it is hoped to provide some illumination of the educational issues raised.

Our world has now perhaps reached a "tipping point" where the results from a computer are more believable than the evidence of our own eyes. A virtual laboratory (VL) gives a particular perspective of the events in a real laboratory experiment. This can be a useful learning tool, but like any tool we need to know how to use it effectively. Over the recent past, education has moved towards a more digitally based delivery of the curriculum (JISC, 2015). One strand of this is the emergence of the VL as a routine teaching tool, particularly in the context of higher education (HE) (Lewis, 2014). While VL have existed for a number of years, recently there has been an increase in sophistication. Some of the newest versions are based in virtual reality, providing an even closer feel of the real laboratory. It has been shown that VL offers a good way for students to develop practical skills, for example, Miller, Carver and Roy (2018) found no difference in learning outcomes compared to real laboratories. However, there is an 'absence of descriptive and qualitative research exploring everyday educational practices using virtual laboratories in naturalistic contexts' (Sellberg, Nazari and Solberg, 2024).

The extension of VL to Further Education (FE) settings has been limited and this area provides the context of this work. FE does present some particular challenges compared to HE, including funding, limited facilities, student motivation and prior attainment (DfE, 2018). However, the recent COVID-19 related closures of educational settings, means that virtual laboratories have become a significant part of the learning environment for some FE students. In a small study such as this it is important to have a tight focus on the questions addressed. I cannot hope to answer the question of what truth is, but in this work tried to provide an illustration of the truth experienced by students studying science in an FE environment.

Since the VL is based on inductive principles, which are assured by a uniformity of nature (Okasha, 2016), learners experience a world which (in principle, at least) is constructed logically to form a whole environment. Educationally, this may be useful as tasks can be scaffolded up through the range of cognitive skills. However, there is a risk of losing the “discovery”, “uncertainty” and “edginess” of an interaction with real materials in the laboratory, removing the ‘liminal zone between problem solving and problem finding’ (Sennett, 2009, p. 48) – a space where real discovery can be made.

An issue is then: can virtual laboratories be seen as a substitute, replicant or enhancement of the real laboratories, when learning about science? One way to investigate this is to ask learners about their experiences. The responses of those learning in these environments provide insights to the learning process. This first chapter is organised into two main sections; the first covering the context of the study and the second the research problem.

Context

Science has a strong experimental background. The use of virtual experiments can provide a learning experience, which is often difficult and expensive to provide in the physical world. This has been particularly relevant since the COVID-19 crisis significantly reduced access to real laboratories.

There are a number of strands which need to be developed to put this work in context, it would be useful to start by trying to set the scope of this research. Clearly, there is a great deal to be said and in order to say something useful it is helpful to have an aim in mind. I would like to address the question: “How useful to learner’s education are virtual laboratories?”. So, this is the destination I am walking towards. There are of course a number of issues when looking at this, including: what is useful (skills, knowledge, behaviours etc.)? What is education? Is further education different? How do we learn? How do we think? Who are the students? What is the learning context? Who are the teachers? what is science? How is it different to other fields of knowledge? What are virtual laboratories? How are they different to real laboratories? What is truth? Most of this is beyond what can be addressed in a simple work such as this. The context is now set out in three main areas: the research environment; science education and virtual laboratories.

The research environment

COVID-19 has brought a rapidly changing educational scene where it is necessary to develop new pedagogy. As part of this process, it is useful to think of how science and the scientific method can be enhanced by novel techniques and perspectives. For students particularly in FE there also is a constant focus on achievement and employability skills, so these must also be added into the mix.

This research focuses on students studying A level Chemistry, at a large FE college in the north of England. The study investigates their experiences in engaging with experiments in both virtual and real laboratories. The students are following the syllabus for OCR Chemistry A (OCR, 2021). The course is assessed by 3 exams, taken during the final term of the second year, and a separate practical endorsement which is continuously monitored over the two years of study. The students following the A level course are largely 16-18 who have joined the course directly from studying GCSEs at school. The minimum entry requirements for chemistry are a 6 in chemistry or combined science GCSE; 4 in English and a 6 in maths; these are not strictly enforced and a few students with lower grades have been enrolled. Most of the students are taking at least one other science subject, particularly biology. The majority of the students intend to progress to university.

Due to COVID restrictions and changes in College's timetabling, the timing and length of lessons changed over the period of this study. The period for practicals and other lessons were 1.5 or 2 hours, with a total of 4.5 or 5 hours teaching per week. The students are expected to carry out a range of practicals during their course; this includes a collection of experiments specifically designed by OCR. These are known as PAG (Practical Assessment Group) experiments. There are 12 groups of three activities (OCR, 2015; OCR, 2021); each group centred on a different set of knowledge and skills. There is a range of skills which need to be demonstrated during these praticals. Students are assessed on a pass / not completed basis and provide a separate practical endorsement to the qualification. The students have the opportunity to demonstrate the skills in different ways over a range of practical activities. As discussed further below, practical science is an integral part of the specification for A level chemistry with a set of specification requirements for practical activities which are detailed by OCR (2021). The students also undertook a number of virtual experiments using the Royal Society of Chemistry (RSC, 2024) virtual titration experiments and several PhET (2024) simulations.

The survey data, recorded from February – May, 2022 comes from two cohorts: the September 2020 (in their second year) and 2021 (in their first year) intakes. The interview data recorded from January to April, 2023, is from students in the 2021 intake in their second year.

Science education

I now want to consider the nature of science education. Science education is in itself a discipline with specific organisations such as the Association for Science Education (ASE, 2024); specific literature, such as Science and Education (2025), the Journal of Chemical Education (J. Chem. Ed, 2021) or Education in Chemistry (Ed. Chem., 2021) and specific undergraduate (e.g. SHU, 2021) and post graduate courses (e.g. UCL, 2021). There is also a vast literature and academic hinterland based around science and education separately. The nature of science is a major and contested topic, which will be discussed in more detail in Chapter 2. In this section, I will concentrate on specific aspects which are closely related to my research questions, being aware that I am only seeing a small fraction of the issues involved.

The English education system is controlled by a set of laws and regulations which informs how science is taught. The wording of the National Curriculum requires (DfE, 2015) all learners:

- *'develop scientific knowledge and conceptual understanding through the specific disciplines of biology, chemistry and physics*
- *develop understanding of the nature, processes and methods of science through different types of science enquiries that help them to answer scientific questions about the world around them*

are equipped with the scientific knowledge required to understand the uses and implications of science, today and for the future'.

An issue which arises is the focus on 'the specific disciplines of biology, chemistry and physics' (DfE, 2015), rather than a holistic approach to all science, producing a siloed mentality. However, the guidance goes on to say that the study should include 'ideas relating to the sciences which are inter-linked, and which are of universal application. These key ideas include:

- *the use of conceptual models and theories to make sense of the observed diversity of natural phenomena*
- *the assumption that every effect has one or more cause*
- *that change is driven by interactions between different objects and systems*
- *that many such interactions occur over a distance and over time*
- *that science progresses through a cycle of hypothesis, practical experimentation, observation, theory development and review*
- *that quantitative analysis is a central element both of many theories and of scientific methods of inquiry'*

(DfE, 2015)

This is the effective definition of science, which "science education" is expected to deliver. Although the National Curriculum only applies until Key Stage 4. There is a requirement that 'AS and A level science specifications must build on the skills, knowledge and understanding set out in the GCSE criteria/content for science' (DfE, 2014). So, we can see that practical science is integral to science education both implicitly as part of the 'nature, processes and methods of science' and explicitly as 'observed diversity of natural phenomena'. It is part of 'a cycle of hypothesis, practical experimentation, observation…' and 'scientific methods of inquiry', which distinguishes science from other disciplines.

Looking in more detail at the Key Stage 5 requirements (DfE, 2014) the importance of practical activities is highlighted at several points, for example:

- 'Specifications in biology, chemistry and physics must encourage the development of the skills, knowledge and understanding in science through teaching and learning opportunities for regular hands-on practical work'
- 'carry out experimental and investigative activities, including appropriate risk management, in a range of contexts'
- 'apply investigative approaches and methods to practical work'
- 'safely and correctly use a range of practical equipment and materials'.

There are a number of points it is worth highlighting, for further consideration, in the context of this research. Firstly, as with the National Curriculum there is an expectation that science is: biology, chemistry and physics. As with the A-levels themselves, there is a clear division between disciplines which in reality does not exist. Three learning outcomes are then identified in the 'development of the skills, knowledge and understanding' gained from practical work. There is also a requirement for 'regular hands-on practical work' which suggests physical interaction with the experimental procedure. Further, there are references to 'investigative activities' and 'investigative approaches and methods', this suggests the activities should have an element of open-endedness and not be fully constrained. There is also a requirement for risk management and the consideration of safety issues which are very much in the physical domain.

In the context of this research these requirements lead to the question of whether some or all of them can be met in the VL? Can we change or adapt the VL to make it cover those points? (The next section discusses the nature of the VL). Also, does this guidance identify the right approach to learning science, particularly through practical activity? What is the aim of teaching science at this level? Is it to provide a feedstock for university science courses, or to provide a more scientifically literate population, or to provide practical skills, or abilities to think and analyse? These questions are outside the scope of this work but are part of my working landscape.

The virtual laboratory

What makes a laboratory?

Imagine standing in your kitchen, weighing out 10 g of sugar to add to yeast, to make a loaf of bread – you are cooking. Imagine standing in a laboratory, weighing out 10 g of sugar to add to yeast, to test the rate of growth – you are doing science. The context and intention of the act give it meaning.

So, looking first at context - what differentiates the kitchen from the laboratory. What differentiates any space as a science laboratory? Is biological field work less 'scientific' because it is carried out in a field or theoretical physics because it grows through the firing of neurons in the brain? Perhaps, we could define the laboratory as the space in which 'science' happens. Of course, we now need to define science, but suppose we can, this still really leaves a definition which is too wide to be useful.

Does the laboratory need to be used exclusively for science, does the space cease to be a laboratory when the scientist stops experimenting, sits down and reads a novel or writes a poem? A school or college laboratory can be a multipurposed space often used for teaching as well as experimental science; so, is the key factor – experimental? For Dewey (1933, p. 49) 'it is not necessary that laboratories shall be introduced under that name, much less that elaborate apparatus be secured; but the entire scientific history of humanity demonstrates that the conditions for complete mental activity will not be obtained till adequate provision is made for the carrying on of activities that actually modify physical conditions, and that books, pictures, and even objects that are passively observed but not manipulated do not furnish the provision require'. So, the laboratory is a space for carrying out experiments - tests, practical activities – that may prove a more useful definition.

There are a range of environments which might be considered as science laboratories. Most people would consider an environment like CERN or a University research laboratory to be science laboratories. So, we could develop a scale from these through college and school labs to the primary school classroom where a class measure their heights, a home chemistry kit, to counting butterflies in a field or stars in the cosmos. This is a focus on the physicality and exclusivity of the space in which science happens. So, perhaps a *definition* of the laboratory, such as the place where practical science is done would be useful. Maybe, where practical science is being done, to include a temporal element. So, a working definition might be a laboratory is "a space in which practical science is happening".

Real or Virtual?

We now need to distinguish between the real laboratory, by which I mean, one in which a student is present as an active participant in an experiment; and other types of laboratory space:

- a remote laboratory, where the student is participating in a real experiment via a link;
- a real demonstration, where the student observing "in the room";
- a remote demonstration, where the student is observing via a link;
- an interactive model, where the student is able to manipulate a physical model;
- a field observation, where a naturally occurring process is observed;
- a simulation, where the results of an experiment are mimicked by another process – generally, a computer program and a student can adjust the parameters to vary the results;
- an animation, a simulation with predetermined parameters and results;
- a VL, where the student is able to construct an experiment using a range of virtual tools.

Clearly, there is some flexibility and overlap between categories and this might be expressed as a diagram of student engagement in terms of presence and agency, as in Figure 1.

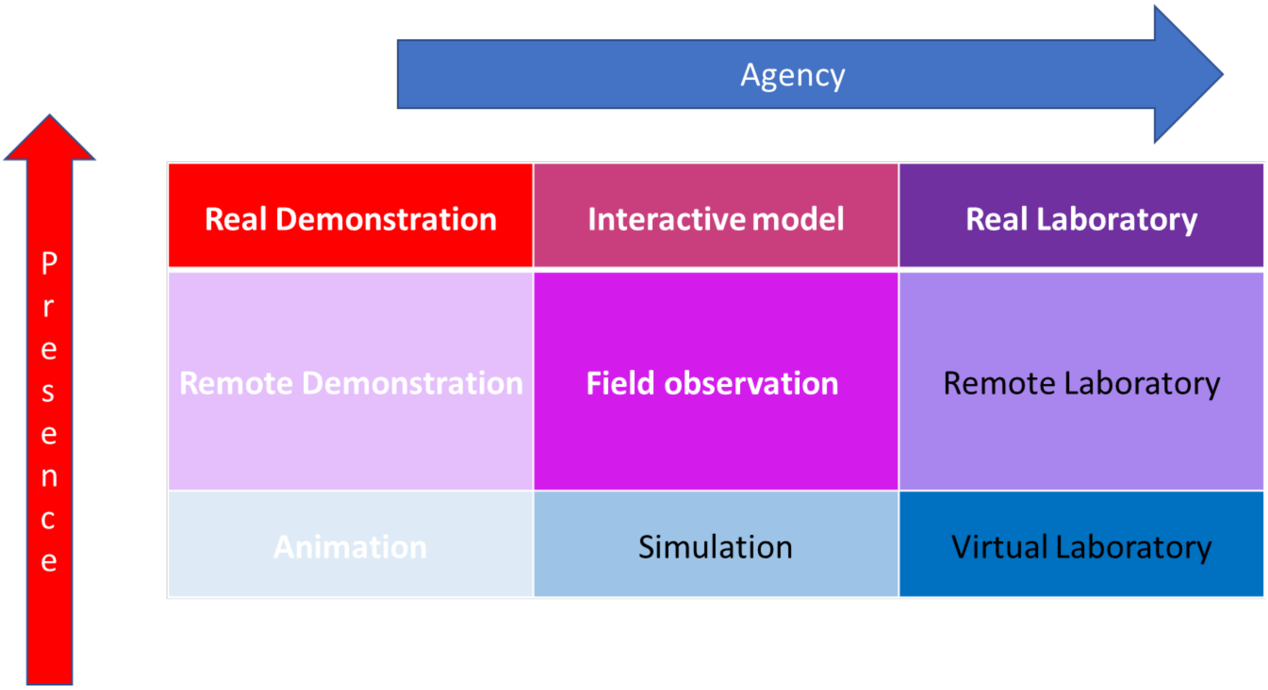

Figure 1 showing the variation in presence and agency for different "laboratory" environments. Where presence and agency are discussed in the text.

By presence, I mean how closely the student is involved – how visceral the interaction. This discussed by Makransky, Lilleholt and Aaby (2017) who suggest, in relation to virtual reality (VR), 'presence as the experience or feeling of being present in a mediated environment, rather than the immediate physical environment wherein one is currently bodily present'. Agency refers to the ability of the student to influence events.

Brandon's Matix

An alternative categorisation of laboratories can be envisaged based on Brandon's matrix (Erduran, Ioannidou and Baird, 2021; Erduran and Dagher, 2014; Brandon, 1994). Brandon (1994) developed a classification of experimental types based on evolutionary biology. He analysed the parameters related to manipulation and hypothesis testing to develop a two-by-two table, which is reproduced in Figure 2. Erduran and Dagher (2014) developed and extended this idea, while Erduran, Ioannidou and Baird (2021) use this framework to analyse the epistemic content of different scientific methods. The authors point out that 'Brandon's Matrix is not rigid, as the matrix can be also be viewed as a continuum between 'more experimental' and 'less experimental' investigations' (ibid), this is shown in Figure 3, based on Brandon (1994).

	Manipulative	**Not Manipulate**
Test hypothesis	Manipulative hypothesis test	Nonmanipulative hypothesis test
Measure parameter	Manipulative description or measure	Nonmanipulative description or measure

Figure 2 'showing the two-by-two matrix formed by two separate distinctions relevant to the question of what is an experiment' (Brandon, 1994).

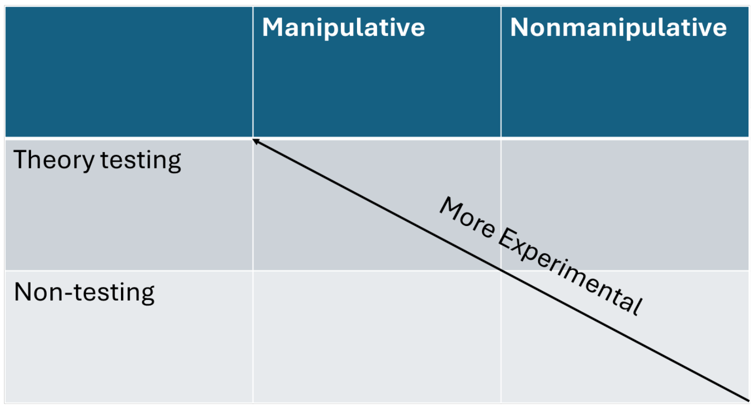

Figure 3 'The representation of the space of experimentality formed by two continua relevant to the question of what is an experiment' (adapted from Brandon, 1994, Fig.4).

This suggests several possibilities in relation to the present study: the recasting of Figure 1 in the form of Figure 2 and Figure 3; analysis of the laboratories shown in Figure 1 using Brandon's matrix; the exploration of the various interplay between the parameters; highlighting of the vector representing variation of "experience"; the construction of a multidimensional matrices to analyse the potential interactions between parameters and the analysis of the types of laboratory within this matrix. These are addressed in turn.

	Lacking Agency	Agency
Presence	Class Demonstration	Real laboratory
Lacking Presence	Animation	VL

Figure 4 showing examples within the two-by-two matrix formed by two separate characteristics relevant to the question of how we experience a laboratory experiment.

	Lacking Agency	Agency
Presence	Present but lacking agency	Present and having agency
Lacking Presence	Not present and lacking agency	Not present but having agency

Figure 5 showing the two-by-two matrix formed by two separate characteristics relevant to the question of how we experience a laboratory experiment.

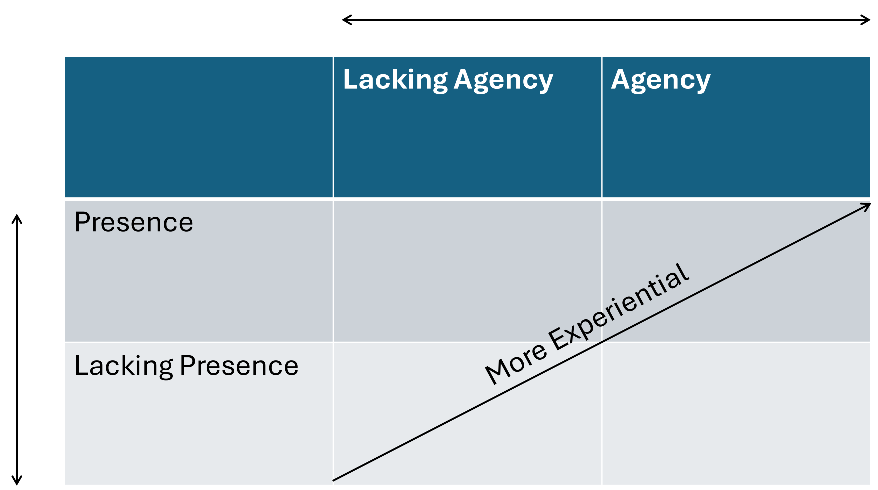

Figure 6 showing the continua between the extremes of the agency and presence parameters, and the direction of the increase of experience.

Using a two-by-by matrix to simplify Figure 1, leads to a matrix form, such as Figure 4, and considering each element of the matrix descriptively gives a matrix such as shown in Figure 5. The more generalised form of the matrix is shown in Figure 6, demonstrating that experience can be thought of as the combination of presence and agency. This illustrates the point that “experience” can be felt due to different factors and that these could be analysed independently. However, applying Brandon’s matrix to the different types of laboratory reveals a significant issue in classification. As Bandon (1994) points out, the *same* data from the *same* experiment can be viewed in relation to different parameters. The intent and experiences of the participant are therefore important. This is a complex area, as for example, one of two students, working together may see a titration experiment as simply *measuring* the volumes at the end-point, the other may have just watched their partner make those measurements and been more interested in showing that the acid-base neutralisation supports the law of definite proportion. Moreover, the teacher may wish to test the hypothesis that Group 2 are better at practical measurements than Group 1. Therefore, Figure 7, can be seen as an example of how different laboratories might be classified, a fuller analysis is beyond the scope of this thesis.

	Manipulative	**Not Manipulate**
Test hypothesis	Real laboratory	Real demonstration
Measure parameter	Real or virtual laboratory, field observation	Any

Figure 7 showing the different types of laboratory experiments discussed in the text within Brandon’s Matrix.

Turning now to the combinations of the parameters from Barndon’s Matrix with those of presence and agency: these are shown in Figure 8 to Figure 10. Each of these could be recast and exemplified similarly to Figure 3 and Figure 6, to show for example the increase in “hands-on experience” shown by manipulative presence in Figure 8 or the feeling of “conformation” from being present when a hypothesis is verified, such as Figure 9. Figure 10 shows the interplay of agency and manipulation, as it is difficult to think of examples off the main diagonal, it would be reasonable to equate agency and manipulation. Thus, the matrices showing hypothesis testing with agency and manipulation with presence have not been included. Using this simplification would result in a three-dimensional set of two-by-two matrices. Equivalent to adding the hypothesis test dimension of the original presence – agency matrix in Figure 2. The use of VL in hypothesis testing is outside to the scope of this work, where the VL is considered as essentially a teaching tool, however this might be a fruitful use of Brandon’s style matrices.

	Nonmanipulative	**Manipulative**
Presence	Present nonmanipulative	Present manipulative
Lacking Presence	Not present and nonmanipulative	Not present but manipulative

Figure 8 showing the two-by-two matrix formed by two separate distinctions concerning presence and the degree of manipulation.

	Test hypothesis	Not test hypothesis
Presence	Present test hypothesis	Present and not test hypothesis
Lacking Presence	Not present and test hypothesis	Not present and test hypothesis

Figure 9 showing the two-by-two matrix formed by two separate distinctions concerning presence and the degree of hypothesis testing.

	Nonmanipulative	Manipulative
Agency	Having agency but nonmanipulative	Having agency and manipulative
Lacking Agency	Lacking agency and nonmanipulative	Lacking agency but manipulative

Figure 10 showing the two-by-two matrix formed by two separate distinctions concerning agency and the degree of manipulation.

In summary, the combination of the presence – agency provides learners with an experience which varies according to the strength of each parameter; this is similar to Brandon's matrix which suggests that the combination of theory testing and manipulation determine the degree of experimentation. Combining the matrices from both approaches can potentially provide further insight into experience within practical science.

Nature of a virtual laboratory

Having considered what makes a laboratory, it now necessary to be more specific about the VL. A VL can be considered as a constructed environment for scientific learning, which exists outside the traditional laboratory space. In particular, I am focusing on the interaction of the user with a computer program. There is now a question about the type of learning which might happen. Is there a difference between research – new learning and learning the 'old' knowledge embedded in the curriculum? For Hanson (1962), there is a difference between the ''catalogue-sciences' of school and undergraduate text-books' (ibid., p. 1-2) and 'the discovery of new patterns of explanation' (ibid., p. 2). The VL is definitely part of the 'normal science' of Kuhn (1996) and the 'finished systems, planetary mechanics, optics, electromagnetics and classical thermodynamics' (Hanson, 1962, p. 1).

The nature of the VL has changed over time, perhaps in the same way that the real experiments performed in school and college laboratories have changed over time. At one time, these were the cutting-edge demonstrations of novel phenomena – the test beds of new ideas. For the experimenters they were uncertain of the outcomes–- each a step into the unknown. As these experiments were performed many times the results become expected – the outcomes known. If the school laboratory results do not match the textbook – students ask, "what has gone wrong?". Often, such as for the A level chemistry PAG experiments (OCR, 2015), students are presented with a method sheet and the teacher a set of expected results. Success is then – the student carrying out the steps in the method and producing the results to match expectations. This process definitely allows students to be trained in the practical skills of following instructions, measurement, observation and recording; but does not ensure more than that? It is the additional questions about why things happen presented by the instruction sheet or teacher which can lead to deeper learning. The same issues apply to VL where instructions and outcomes are even more tightly linked. Indeed, for some VL programs students are returned to an exercise where they have not “correctly” completed the task – they are not allowed to fail. This leads to a pedagogical monolith, which eliminates the possibility of different perspectives. The next sections introduce some of the ideas and concepts concerning VL which will be developed further in this thesis.

Patterns and schema

In Chapter 2, the argument will be developed that the nature of the VL requires that knowledge is passed on in the form of patterns and so pattern recognition is an essential part of learning in these environments. The VL is an environment which has an imposed form, in which there are a set of patterns which define the user’s interactions. The options are limited in a VL environment to certain ‘allowed’ actions; just as in the real world actions are governed by the ‘laws of nature’, so the VL is governed by the programmed environment. This means that some patterns are allowed – others are not. It might be argued that the learning occurs in the interaction of these patterns with the patterns or schema already present in the learner’s ‘vocabulary’. Bartlett (quoted in Brewer and Nakamura, 1984) define schema as ‘an active organization of past reactions, or of past experiences, which must always be supposed to be operating in any well-adapted organic response’. Brewer and Nakamura (1984) identify Bartlett’s ‘hypothesis that schemas are complex unconscious knowledge structures’ as central to his contribution. Here we can relate this to the VL which relies on such knowledge structures in building a plausible environment for the learner. Further, Brewer and Nakamura (1984) note that Bartlett states ‘that the term ‘pattern’ would not be quite accurate, since it implies more detail than he intended’. It might be argued that in the case of VL the mathematical nature of the constructed environment leads to this detail; so, we would be justified in using the term pattern in place of schema. Gestalt psychology, which recognises the importance of the form and pattern (Wertheimer, 1923), is also discussed in Chapter 2.

Theory

The relationships between observation, data, theory and interpretation are important in this work, and these are considered in Chapter 2. For now, it is necessary to realise that a VL must be based on a theory or theories. There are underlying ideas and assumptions which dictate the way a VL works. These are governed by the theories which are used in the construction of the VL.

The VL is based on logic and a theory or theories can be identified which operate in a particular VL. These theories govern the behaviour of the VL. It is the choice of the theoretical principles which lead to the eventual “reality” created within the VL. There is a really important point here, that the VL is governed by the theory – whether or not that theory is appropriate or correct. As with all digital environments the rule – ‘garbage in – garbage out’ (DCS, 2016) applies. When we are using VL as a learning tool, we must be careful to identify the appropriate theories to facilitate the learning we want to achieve. How closely do we wish to match “reality”? (A fuller discussion of the nature of reality is postponed until Chapter 2, but here we use the everyday concept of ‘the state of things as they actually exist’ (OED, 2021).) Are we trying to match the total experience or do we want “edited highlights” which match the learning aims? This is related to the type of learning we wish to achieve, which in turn is related to the educational theories which underpin our pedagogy; again, this is explored in more depth, in Chapter 2.

Rules

We are using "rules" here in the sense of statements which are derived from a theory. They are a direct and logical consequence of the theory. For a simple case, they are really just a re-statement of the theory, possibly as an equation. For example, Ohm's law states that the current is proportional to the voltage: a rule would then be the voltage (V) equals current (I) times resistance (R) or V = I R. In a more complex case, such as a chemical reaction, one rule might tell us which chemical in a mixture will react at a particular rate with a reactant A and another rule the rate with B; while another the rate of colour change as a new product is formed. Clearly, many layers of complexity may be present if we are to replicate the real world.

Models

Science is often developed by the use of model systems. The set of rules, derived from theory, will generate a model system. In these model systems a particular theory or set of theories are assumed to apply, other effects are excluded from the model system. The system then responds or develops according to that model, (other effects may be added to the system as corrections or perturbations to the model). A VL is a total model system, which is run according to a set of rules, and it is these which determine the nature of the virtual world the learner experiences.

Algorithms

Algorithms in this case refer to the transition vehicles, converting rule-based models into a mathematical form. They are programmed to produce a virtual outcome to a set of inputs to the VL. The algorithm is the mathematical incarnation of the model.

Existing virtual laboratories

There are a wide range of virtual laboratories which have been developed over the past few years some of these are free (see ChemCollective (2024), MERLOT (2024), MSU (2024), PhET (2024), RSC (2024)) and some commercial (Labster (2024), Beyond Labz (2024), PraxiLabs (2024), VPLAB (2024), FlashyScience (2024)). This work focuses on the RSC (2024) titration experiments, discussed in Chapters 3 and 4.

Problem

Science has a strong experimental background (Holman, 2017) and the use of virtual experiments can provide a learning experience, which is often difficult and expensive to provide in the physical world. For science, Dewey (1933, p. 49), tells us, 'Effective and integral thinking is possible only where the experimental method in some form is used'.

Virtual Laboratories in FE

The COVID-19 crisis has meant that my College had to respond with some speed in providing much of the curriculum across subjects and disciplines in a blended learning format. In the process, virtual laboratories have become part of several of the College's science courses. These allow students to access practical science activities when physical laboratories are restricted. VLs also provide opportunities for enhanced practical learning, supplementing and consolidating physical experiments.

The VL is a developing tool which is now reaching the point of routine implementation in some HE institutions. However, context is important, so the educational value of VLs should be explored over a wide range of settings with students from a variety of backgrounds. To date, there is limited evidence for the value of VLs used with mixed ability students in an FE setting. Additionally, not much is known about how the students experience learning in a VL. A recent review by Sellberg, Nazari and Solberg (2024) suggest 'that there is a need for more in-depth empirical studies on everyday teaching and learning practices using virtual laboratories, and the conditions under which students develop their knowledge through these tools, in order to productively inform future policymaking in this growing and important field'. While, there are a few studies reported in HE (for example, Caño de las Heras et al, 2021), there are no peer reviewed studies in the FE context. Similarly, questions of the extent to which students experience learning in a VL as a mirror of reality and how trustworthy they regard the results of experiments conducted in that environment are not yet well understood or reported in peer-reviewed literature, particularly in the context of FE. This raises the question of how much confidence teachers can have in the educational value of learning in VLs.

The changing nature of the virtual laboratory

The genesis of VLs can be traced back to the simulation of experimental results in research situations (see Hut, 2006). Computer programs were developed to analyse results from experiments based on a theoretical model, for example, linear regression. Graphical, as well as, numerical outputs can show the goodness of fit to the experimental data. This involves calculating the results of a simulated experiment and adjusting the parameters to fit as closely as possible the experimental results. This is the basis of many studies including some in which I have been involved (Moore et al, 1988; Mortimer et al, 1989; Mortimer et al, 1992; Moore et al, 1993; Mortimer et al, 1996). It is a natural development to simulate the experiments, based on the models developed in these types of studies. The model is now used in a predictive way to suggest what might be seen in a future experiment. After a period of time and repeated tests, it becomes apparent that the model will give reliable, if not perfect results. Since, researchers use simplified model systems to investigate more complex problems, there is a tendency to identify the dominant effects in a set of experiments. Then simplify a set of observations to identify a manageable number of important parameters. Once this is done a model system can be developed and used to explain and predict the data.

At this point we are able to move from the 'research phase' to the 'education phase', now the simulation can be used separately from the real experiment as a tool for learning. This is an important transition because now we are learning about the *simulation* not the original experiment which it models. There are many reasons for doing this some of which have already been discussed. However, it is in this transition that a fundamental problem arises. We are one step further from reality (a concept which is further discussed in Chapter 2), and so experience is mediated through the simulation – model – theory.

The models often start as empirical, matching data to changing variables and from these more abstract theoretical models are developed. Eventually, a theoretical model is established which can be tested by establishing a formula – a quantitative expression, this in turn can produce a numerical algorithm. The result is a 'black box' into which initial data is supplied and an answer produced. Weisskopf, (Sennet, 2009, p. 41) cautions MIT students that 'When you show me the result, the computer understands the answer, but I don't think you understand the answer': this even more the case for FE students.

Researchers working in the field and developing ad hoc software to simulate their own experiments have a direct connection to the data, they have a "feel" for the correctness of a result. They have a consciousness also for the limits over which a model might be applied. This is a theme taken up by Sennet (2009, pp. 227-235) who talks about 'sites of resistance' and the active nature of boundaries. For those who 'understand the answer' these are valuable places of learning- but what of the rest?

So, from these research-generated models: researchers, then post-graduate students, lecturers, undergraduates, teachers and learners in schools and FE colleges, have over time, learnt of how the world works: rather, how one model of the world works. Through this journey the model is re-purposed, no longer in a tight frame bounded by secure knowledge and experience, but given as a solution to the problem, which may not be that well understood. Sennet (2009, p. 198) remarks on the difficulty in using fine tools and learning to use them to best effect. He continues to consider the repurposing of tools, which aligns with the repurposing of the computer simulation into a VL.

A question which needs to considered is what is the purpose of the VL? Has it been developed as a research tool and now repurposed as an educational tool? Is the simulation a suitable tool for repurposing in the sphere of education? There are many examples of VL aimed at educating students, both free to use and commercial offerings. Are these the best tools to do the job? Then what is the purpose of the VL is it to provide a replicant of the 'real' laboratory. If we consider the real laboratory where is its origin? These questions will be investigated further, in Chapter 2, in the light of a number of thinkers in the fields of the philosophy and history of science, the philosophy and application of education and the specific area practical science education.

Mapping the remainer of the thesis, Chapter 3 sets out the methodology for this study. Chapter 4 is concerned with data analysis and emerging themes. In Chapter 5, there is a more detailed discussion of themes and findings. Finally, in Chapter 6 conclusions are drawn based on the emerging themes and recommendations are made.

CHAPTER 2

UNDERPINNING IDEAS

'Experience by itself teaches nothing…Without theory, experience has no meaning. Without theory, one has no questions to ask. Hence without theory there is no learning.'

(Deming, 1994, p. 103)

Introduction

In this work I am concerned with practical science, both real and virtual. This leads me to consider what is meant by science – does it differ from other forms of knowledge; can we talk of science and non-science? Is practical science different and distinct or is there little sense in separating theory from experiment? What are reality and truth – how do these link to the concept of a virtual space?

This chapter starts with a review of virtual laboratories, in particular, what current research can tell us about student experiences of learning within VL environments. The remainder of the chapter explores three broad themes: the nature of science; the value of practical science and the application of science education. Each is considered in relation to the concept and implementation of virtual laboratories.

Virtual Laboratories

Development of Virtual Laboratories

A brief history of simulations, used in education, is provided by de Jong (2016). This can be traced back to 19th century wargames and early 20th century flight simulations. Many of the early simulation programs focused on physics topics. Towards the middle of the 20th century medical and business simulations were also developed. By the late 1970s computer-based flight simulators were available. The emphasis of most of the first computer-based simulations was practical skills training, with little in-built guidance. During the early 1980s, programs started to include student guidance and there was a growing emphasis on understanding models and conceptual knowledge. One of the first purely educational programs was based on economics, in which students could investigate the effects of supply and demand in a simulated market. As the applications increased, it was recognised that scaffolding increased the educational value of these programs.

Current Virtual Laboratories

There is a wide range of VLs available, these can be grouped into subject areas, style of delivery, complexity, transferability, ease of use and cost. At present, there appear to be three major commercial software suites available: Labster (2024); Praxilabs (2024) and Beyond Labz (2024). There are also some subject specific commercial offerings such as FlashyScience (2024) and VPLab (2024) for physics; Yenka (2024) for chemistry. There are also a large number of free VLs available, many are *ad hoc* produced by academics or organisations, however some major collections such PhET (2024), MERLOT (2024) and Amrita (2024) have been developed. A list of available VLs is given in Appendix 1; this is not intended to be comprehensive but provides a snapshot of the current provision.

Studies of the implementation of VL

There have been a number of studies of the application of VL, these have mainly been focused on HE; for example, reviews by Price and Kirkwood (2011), Lewis (2014); Brinson (2015), Heradio et al (2016), Potkonjak et al. (2016), de Jong (2016); Makransky, Thisgaard, and Gadegaard (2016), Lynch and Ghergulescu (2017), Miller, Carver and Roy (2018), Sypsas and Kalles (2018), Kennepohl (2020), Sypsas, Paxinou and Kalles, (2020), Zendler and Greiner (2020), Kelly (2021), Wörner, Kuhn and Scheiter (2022), Govender (2023), Sellberg, Nazari and Solberg (2024). Generally, these reviews and studies have found similar learning outcomes for learners in VLs compared to real laboratories. There have, however, been a limited number of studies of VL in FE in the UK. I am only aware of two: Marshall (2012) and Peirson (2020).

Studies in FE

Marshall (2012) reports the use of interactive screen experiments (ISE) for AS biology students in a large UK FE college. These students appear a comparable cohort to my first year A level students. In the study Marshall (2012) suggests that student feedback 'can be divided into five broad themes: confidence, preparation, independence, familiarity and design of the ISE'. She notes '...most students thought practical work was important in science'. Marshall (2012) gave one group of students experience with the ISE, prior to laboratory work. She found this group 'did perform slightly better than the group who had not used the ISE'. Students commented that since you 'can prepare yourself for lessons and equipment before you use them', this 'makes you feel more comfortable' and 'so, you know it looks right.' Therefore, for some students the ISE was useful in *improving experimental skills*. A second theme identified by Marshall (2012) was that students found the ISE 'enables independent learning' allowing them to 'read ahead or catch up with missed work'. Marshall (2012) also found some negative attitudes such as: 'boring' and 'confusing, I don't like learning in that way'. Marshall (2012) concludes from her study that 'ISEs are a useful tool for teaching practical skills in science' and 'improve the experimental skills of students'. In the other FE study, I report on a prior study of VL in my College (Peirson, 2020) and this article is included in Appendix 2.

Studies outside FE

Comparison of results from VL education

Beyond the FE context, de Jong (2016) also reviews a number of studies comparing simulation-based learning to both 'traditional methods' (e.g. lectures) and real laboratories. The overall conclusion is that 'simulation-based learning environments show advantages of simulations over traditional forms of expository learning and over laboratory classes'. However, de Jong (ibid) offers a number of caveats; firstly, there is a difference in the type of knowledge developed in different environments with a suggestion that simulations are particularly suited to the transfer of conceptual or implicit knowledge. Secondly, that most studies do not take into account individual differences between participants. There is evidence that gender, level of prior knowledge and spatial ability, may affect outcomes. Similarly, while the study by Colorado DOHE (2012), shows no significant difference in overall outcome (grade point average, GPA) between online and traditional course delivery (including VL) over a four-year programme; it does highlight a difference between subjects within specific courses. Both biology and chemistry show higher grades for traditional methods, unlike physics which shows no significant difference. These studies indicates that care needs to be taken when generalising results, and that quantitative data need to be viewed with caution. Additionally, a study by Wolf (2010) provides some preliminary evidence that learning in a VL is as effective as in lectures, although the methodology is not conclusive. Crandall et al. (2015) also found little difference in outcomes between real and VL, but noted that students who favoured the VL appreciated the ability to work at their own pace, while those who preferred the real laboratory – valued group work and access to instructors. While Thisgaard and Makransky (2017) found similar results for high school students, where 'virtual learning simulations are at least as efficient in enhancing learning and self-efficacy as traditional lessons'. Similarly, Kapici, Akcay and de Jong (2019) studying middle school students, found the VL provided comparable learning opportunities and an enhancement using a combination of methods.

Combinations and sequencing

de Jong (2016) also highlights the importance of instruction and scaffolding as an essential part of the implementation of VLs. The instruction method can take several forms depending on the intended outcome of the exercise, but it is 'is very clear from the literature is that unguided simulation based learning is not effective' (ibid, p. 451). While Miller, Carver and Roy (2018) propose providing 'a training session to allow students the opportunity to adjust to the application or virtual format'. Quoting the work of Pyatt and Sims in 2012, they suggest that 'this will decrease the learning curve', so, 'enabling students to focus on the content' (Miller, Carver and Roy, 2018, p. 65).

Helpfully, de Jong (2016, p. 455) provides a useful summary in 'that students need support in identifying relevant variables, that hypotheses could best be provided in a 'readymade' way', and 'that training on experimentation heuristics … general structure for the inquiry process … concrete assignments, and … reflection' are important features. The relevance of timing of instruction is not clear from the studies de Jong (2016) evaluates, he finds insufficient evidence concerning the development of a series of experiments to conclude if and when scaffolding should be reduced.

Hatherly, Jordan, and Cayless (2009) and Nolan et al (2013) describe what they call ISE. These are an interactive version of the virtual experiment in which versions of real experiments are recorded photographically and then software is used to manipulate different outcomes. Nolan et al (2013) found for HE physics students, that 70 % find the ISE useful 'as preparatory tasks … [which] helped my understanding of the experiment.' While Babinčáková and Bernard (2020) also found that a mix of approaches enhanced learning when using VL as part of the mix. Similarly, Tauber, Levonis and Schweiker (2022) found using a VL to precede a real laboratory produced better outcomes than a VL alone. However, their study did not appear to account for the extra 3 hours study time afforded by attending the laboratory session. Nolan et al (2013) use ISE as preparative tasks and found these to be useful both before a real laboratory session, to provide skills training, and afterwards, to aid write-ups. Similarly, Hamed and Aljanazrah (2020) found that students using a VL acquired a 'deeper understanding of physics concepts and were better prepared for carrying out real experiments'. They found their learning was as effective and that students appreciated the flexibility of the VL. While a review by Govender (2023) found that VL 'improved learning, motivation, and knowledge development'. Additionally, Dalgarno et al (2009) found that the VL was a useful preparation for the real laboratory reducing anxiety; they suggest that the inclusion of scaffolded mathematical tasks to the VL would be of added benefit.

Caño de las Heras et al (2021) describe HE students experiences comparing real and VL experiments in fermentation. They find students valued the opportunity to use the VL as a preparatory or supplementary tool. Students also liked the reduced the time needed for VL experiments and this increased their engagement, however, this was reduced for longer VL experiments. Students did not like the lack of social interaction in the VL and could become frustrated by the limited options for further investigation – this was negatively 'affecting motivation and the feeling of control' (Caño de las Heras et al, 2021).

Sypsas, Paxinou and Kalles (2020) reviewing inquiry-based learning with VLs, also suggest that these are best employed in conjunction with real laboratories. They find the learning activities seem to be most successful when initial guidance is provided and open-ended inquiry is only appropriate for the more advanced learners. Further they maintain that a 'crucial part of laboratory success is the instruction design by the educators when inquiry learning is deployed'. A recent review by Wörner, Kuhn and Scheiter (2022) reported a systematic review of 42 experimental studies. The authors address two research questions:

'(1) What is the relative effectiveness of combining real and virtual experiments compared with a single type of experimentation?

(2) Which sequence of real and virtual experiments is most effective?'

The general conclusion of this review is that in most cases it is more effective to combine real and VL experiments, however there is no clear evidence of in what order this should be done.

Learning experience

Miller, Carver and Roy (2018) studied HE students following a physical science laboratory course. They allowed students to choose to complete practical activities using either real or virtual laboratories. They found that students chose the VL for reasons which were 'purely due to convenience' (ibid, p. 65). While the real laboratory was favoured by those who wanted to 'ask questions in person' and … felt that they 'learn better with hands-on' methods' (ibid, p. 65). They state 'that virtual laboratories were as effective with student knowledge gains as the traditional f2f laboratories' and 'that no significant difference between the two groups attitudes/preferences' (ibid, pp. 64-65). However, later they state, that 'these findings are similar to what Stuckey-Mickell and Stuckey-Danner (2007) found in that students prefer hands-on activities and person-to-person interaction with the instructor'. These authors do indeed report a student preference for real laboratories over a range of criteria, in this case for biology students. They also find that 'many students did not perceive the virtual labs as real 'hands-on' learning' (Stuckey-Mickell and Stuckey-Danner, 2007, p. 109). While both these studies use mixed method surveys, with Likert scales and more open questions (see also my earlier work (Peirson, 2020)); Miller, Carver and Roy (2018) conclude that it would 'be advantageous if more studies gathered qualitative data in assessing the value of virtual laboratories' (ibid, p. 65): this study attempts to go some way towards this aim.

Serafin and Chabra (2020) considered the 'emotional satisfaction' of each method finding 100 % preference for the real laboratory. The VL also generated the greatest 'anxiety' (90 %) and the least 'educational growth' (30 %). The authors comment that no definite conclusions can be drawn as the effects of the COVID-19 pandemic, may well have influenced these findings.

Kelly (2021) reviewing 91 published articles on chemical education, concerning the switch to online during COVID pandemic, finds that students report they 'learn more and [were] more engaged when learning in-person with labs than when remote'. While, Reeves et al (2021) explored VR laboratories, reporting that 'four qualitatively different experiences were discovered, which included:

a) VR Labs hindered my ability to learn

b) the amount of content knowledge I have and/or my prior experience influenced my learning

c) the affordances I perceived enhanced my learning and

d) VR Labs removed barriers I perceived to learning.'

This section suggests that as for the results of the VL studies that the responses vary between learners. On balance there appears to be a greater learner preference for the real laboratory although none of the studies appears to have identified a single cause. There have been insufficient studies to satisfactorily establish the importance of different factors on learner experience.

Learning outcomes

Zendler et al (2018) consider knowledge processes involved in learning and apply these in research that compare instructional methods including virtual laboratories. They provide definitions for the elements of a three-stage process for 'the acquisition of knowledge (build, process), in the transformation of knowledge (apply, transfer) and in the evaluation of knowledge (assess, integrate).' They are as follows:

'• ***build***: Acquiring knowledge, new practical and cognitive abilities as well as attitudes;

• ***process***: Establishing, deepening, structuring and connecting what has been learned;

• ***apply***: Using what has been learned in new tasks corresponding with the framework conditions of the learning situation;

• ***transfer***: Using what has been learned in new situations in which the framework conditions differ from those of the learning situation;

• ***assess***: Classifying what has been learned in regard to its usefulness, scope, benefits and limits;

• ***integrate***: Integrating what has been learned outside of the actual learning situation in connection with one's own knowledge.'

These categories are used by Zendler and Greiner (2020) to compare different instructional methods (cf. Hattie, 2012) and find that on average the 'computer simulation' (VL) is slightly more effective than the 'experiment method', in the school classes they studied. The analysis of these methods by STEM teachers, highlights that the experimental method is good for *process* while the simulation for *apply* and *transfer*. This suggests the learning process is different between the two methods and so we should not expect a substitution of the VL for a real laboratory to yield equivalent results. This difference in the strengths of the techniques leads the authors to suggest these are 'seen as complementary instructional methods' (Zendler and Greiner, 2020, p. 17).

Serafin and Chabra (2020) use a 'Cooperative Learning' approach which they define as 'active learning … where a small team works noncompetitively on a task in a structured environment'. In a very limited study (10 participants), the authors show this inquiry-based method can be used effectively for VL experiment; however, they find VL is less effective than real laboratories. This seems to be related to the specific activities (e.g. serial dilution) which was not effectively covered in the VL used but could be in the more flexible real laboratory. This highlights the requirement for the VL to be part of a carefully planned implementation. However, the authors believe 'that properly structured physical experimentation is superior to virtual experimentation', but they do offer some suggestions to improve the VL experience.

Summary

A point of concern when considering these reviews is that there is a range of experiences which are gathered under the heading of VL, VR or NTL (non-traditional laboratories). Some reviews have included remote video experiments (e.g. Brinson, 2015); while others have concentrated on ISE (e.g. Nolan et al, 2013) and others concentrated on just VL (e.g. Miller, Carver and Roy, 2018). This lack of agreement in definitions makes comparisons between studies more difficult.

So, in summary, these reviews suggest that VL is best employed as a complementary method to real laboratories, where it can enhance learning rather than as a substitute. The range of different types of alternatives to the real laboratory is also an area for consideration. These factors suggest that quantitative comparisons between methods will be very difficult to carryout reliably. By adopting a more qualitative approach in the study described in this thesis it is hope that some of the more important factors can be highlighted.

Theoretical discussions of Virtual Laboratories

This next section is concerned with theoretical discussions on the role of virtual laboratories in science education. This discussion will be distinct from those above and focuses on illuminating some of the underlying features through different theoretical frameworks.

Zendler and Greiner (2020) comment on the positioning of methods within specific learning theories. They suggest that (real) experimental methods are in the 'context of the cognitivist learning theory' while computer simulation within that of the constructivist learning theory. While, de Jong (2016) discusses three theoretical approaches which are useful when analysing the educational role of VLs. The first involves the inquiry cycle of 'hypothesis generation, experiment design, data interpretation, and reflection' or problem solving in a 'problem space' (ibid, p. 449). These processes can lead to 'deeper learning outcomes' by activating 'relevant prior knowledge' and encouraging knowledge restructuring. The second approach recognises that VLs provide 'multiple representations' of information in the form of animations, graphs, tables, audio etc., which encourages translations between these representations, 'leading to deeper and more abstract knowledge' (ibid, p. 449). The third perspective is derived from the recognition that 'interactive visual information has the advantages over textual information of being more easily remembered' (ibid, p. 450). de Jong (ibid) also points out that the ability of users to repeat activities many times, since 'an element of practice is necessary in the learning of skills'. 'They are not necessarily designed for novices who are trying to learn about a domain in the first place. Pedagogical simulations may require additional features to support learning'. de Jong's research tells us 'that simulation-based inquiry learning can be effective if the learners have adequate knowledge and skills … and if they are provided with the appropriate scaffolds and tools' (ibid, p. 459).

A number of other theoretical approaches have been applied, several of which are now discussed. For example, Lindgren and Schwartz (2009) consider the importance of spatial learning when using computer simulations. They reject the argument that cognition is 'amodal' – that is it does not matter what form the information is presented and claim there is an inadequate vocabulary to describe spatial factors. These concepts link with those of Gestalt philosophy, which are discussed below. The authors then identify four effects which are relevant to 'spatial thinking and learning'.

These are:-

1. 'The picture superiority effect' – humans have needed to navigate and manipulate tools, relying on visual elements.
2. 'The noticing effect' – as you become familiar with a situation you notice more. Experts become able to notice important subtleties.
3. 'The structuring effect' – perception differing from sensation; because perception is structured experience.
4. 'The tuning effect' – perception is related to action and the motor system, leading to recalibration of perceptual expectations and motor activity (ibid, p. 421).

The authors describe how each of these criteria can be related to VL simulations. These can be seen in relation to the Gestalt principles which are discussed in Chapter 3 and applied in Appendix 19.

Nolan et al (2013) analyse the ISE protocol using Laurillard's (2002) 'good conversational framework'. From this they suggest that ISE only fits well with one of the four criteria, 'operate at the level of action within related tasks' (ibid, p. 27), when considered in isolation as a preparatory task. However, there is a much better fit, with the other criteria concerned with constructive dialogue, interaction, reflection and a holistic description, when used as part of a complete practical activity where the ISE is a preparatory activity. Alternatively, Christopoulos and Pellas (2020) have proposed a four-dimensional theoretical analysis based on 'a mutually-enriching and constantly-interacting relation' between the fields of Technology, Pedagogy, Psychology and Learning Analytics, which they suggest will 'develop a deeper and more detailed understanding' of student learning with VL.

As a result of an extensive literature review, Kelly (2021) has proposed a 'Laboratory Action-Based Theory' for work in the (real) laboratory involving five steps:

'(1) exploration of materials and techniques,

(2) ability to do lab work,

(3) sensemaking of what was done in the lab,

(4) ability to propose future lab work,

(5) desire to continue doing lab work.'

This is a cyclic process returning to stage (1). Kelly (2021) expands this framework to produce a pedagogical model integrating laboratory and 'non-laboratory experiences', urging 'thoroughly integrating effective technological or interpersonal interactions with the core design of laboratory courses.'

Brinson (2015) has developed a tool for the analysis of review data. The learning outcomes achieved using both real and virtual laboratories were identified using the six category 'KIPPAS' method (see Table 1). This framework is used to analyse, and code 56 articles comparing traditional (TL) and non-traditional laboratories (NTL): the NTL includes VL, but also remote laboratories. The results show that most studies focus on assessing the gain of 'knowledge and understanding'; with about half considering 'perception'; the other categories were considered in less than 20 % of the studies. Analysis of the assessment tools shows that these are mostly carried out using quizzes and exams, which Brinson (2015) laments, 'are ubiquitous in science classrooms around the world' it seemingly perpetuates the myth that science is, in fact, a body of conceptual knowledge more than it is a systematic way of thinking and observing the natural world'. Observation and interviews only contribute to the 20 % of the studies, which leaves a gap in the understanding of many of the outcomes which we might wish to achieve. Moreover, Brinson (2015, p. 228) concludes 'Studies supporting higher achievement in NTL seem to place a lot of emphasis on content knowledge and understanding (and thus quizzes and exams as the instrument of assessment), whereas studies supporting higher achievement in TL seemed to rely heavily upon qualitative data related to student and/or instructor perception (and thus surveys as the instrument of assessment)'. Clearly, this must be taken into account when considering the mainly qualitative data reported in this thesis.

Rau (2020) has reviewed 54 articles to identify the underling theoretical perspectives 'used to motivate comparisons of representation modes' and to investigate conflicts and alignments of predictions based on these. Rau describes five perspectives which are now briefly examined.

Firstly, 'physical engagement', this is the 'hands-on' approach, which has been shown in a number of studies (see Rau 2020) to increase students' engagement and yield 'higher cognitive learning outcomes' (ibid.). She concludes that 'physical representations are generally more effective than virtual representations' (ibid.) when viewed from this perspective.

Table 1 showing the KIPPAS criteria, adapted from Brinson (2015, p. 223)

Learning outcome	Description	Lab goals
Knowledge & Understanding	The degree to which students model theoretical concepts and confirm, apply, visualize, and/or solve problems related to important lecture content	Enhancing mastery of subject matter
Inquiry Skills	The degree to which students make observations, create and test hypotheses, generate experimental designs, and/or acquire an epistemology of science	Developing scientific reasoning; Understanding the nature of science
Practical Skills	The degree to which students can properly use scientific equipment, technology, and instrumentation, follow technical and professional protocols, and/or demonstrate proficiency in physical laboratory techniques, procedures, and measurements	Developing practical skills
Perception	The degree to which students engage in and express interest, appreciation, and/or desire for science and science learning	Cultivating interest in science and interest in learning science
Analytical Skills	The degree to which students critique, predict, infer, interpret, integrate, and recognize patterns in experimental data, and use this to generate models of understanding	Developing scientific reasoning; Understanding the complexity and ambiguity of empirical work
Social & Scientific Communication	The degree to which students are able to collaborate, summarize and present experimental findings, prepare scientific reports, and graph and display data	Developing teamwork abilities

A second perspective is that of cognitive load, this proposes that the 'human capacity for cognitive processing is limited' (ibid.); with working memory limited to 7 (± 2) chunks of information (ibid.). There are two design principles which have been proposed to reduce cognitive load (ibid.). These are, the contiguity principle, to avoid multiple sources of information which can split students' attention; and the coherence principle 'recommends eliminating surface features … that are not relevant to the target concepts and could distract students' (ibid.).

The third theory identified is that of haptic encoding, this is related to how the sense of touch allows 'more explicit connections between the perceived environment and the target concepts' (ibid.). Three mechanisms have been proposed for this process: if there are visual cues as well as haptic there is an increase in the number of retrieval cues available; haptic encoding can increase the perceptual grounding of features, which is related to the abstraction process from physical experiences; also, haptic cues can increase cognitive capacity, by providing an additional haptic mode for cognitive processing (ibid.).

Embodied action schema provide a fourth theoretical perspective. This suggests that 'body movements influence cognition' and that 'students form mental simulations that are grounded in such embodied action schema' (ibid.). This perspective in most cases has been shown to favour the physical representation, as these allow for 'moving the body in ways that are synergistic with mental simulations of target concepts' (ibid.). However, some studies have shown that observing or imaging movements may produce similar effects, so it may be the nature of the actions rather than the mode of representation which is significant.

The fifth effect considered is conceptual salience, this has three different aspects. Firstly, information processing studies suggest 'that students have to explicitly attend to information in order to process it in working memory' (ibid.). Highlighting a feature makes it more salient and if it is the 'to-be-learned concept, it is conceptually salient'; this is recognised as a particular virtue of VL. The second aspect is derived from affordance theory. This suggests students subjectively perceive both physical and virtual 'representations as allowing for certain actions that … achieve certain goals. That is, … not … the objects themselves but their affordances for action' (ibid.). It has been suggested that since VL representations allow for different actions they provide a different, and often complementary, affordance. The third aspect focuses on conceptual change that 'challenge their preconceptions' (ibid.). Physical and VL differ in that they emphasise the salience of different aspects, so induce different levels of conceptual change.

Summarising her review, Rau (2020) suggests that there are a number of conflicts between perspectives. Three of the perspectives: haptic encoding, embodied action schema and conceptual salience appear to have concept-specific predictions, which favour either physical or virtual representations in particular instances. While the physical engagement perspective tends to emphasise the value of the physical representation and the cognitive load perspective favours the virtual representation (ibid.). Rau (2020) concludes that 'comparison of the different theoretical perspectives suggests that multiple mechanisms co-occur while students learn with physical and virtual representations' (ibid.).

In a recent review article Sellberg, Nazari and Solberg (2024) point out that most studies do not 'explicitly adopt a theoretical position'; however, they do identify three theoretical perspectives: embodiment and experiential learning, social cognitivist and constructivist, which appear in the studies they reviewed. The studies reviewed appear to be mainly of VR VLs, which account for the first two perspectives: the constructivist approach seems to be applied to a screen based VL.

In general, the theoretical approaches fit into a constructivist framework (Zendler and Greiner, 2020; Govender, 2023; Sellberg, Nazari and Solberg, 2024) of a developing cycle of learning. So, we see VL can be used as a tool for learning a particular part of the 'role' of being a scientist. However, the VL does not provide all the components found in the real laboratory. The question now arises – does this matter? Is the traditional practical science laboratory 'special', or just the familiar way we have taught science? Why does practical science have a particular place in the education system, with designated space and staff, gathering primary data; while other subjects, rely on books and videos? The next section explores the value of practical science, a topic which will be important in the research presented later in this thesis.

Practical Science

Introduction to practical science

Science is in a very real sense a practical subject; so in this section, the concept of science as a practical activity is explored. For example, why do we carry out activities with students which are more expensive, time consuming and in some cases potentially dangerous, than other teaching methods? The question is then can the VL provide a suitable substitute or possible enhancement for some of these activities? The research discussed above suggests that the mode of learning itself – that is to say, face-to-face in laboratory or online in a virtual environment – is important in determining the learning experience. So, to explore this issue further, we need to explore the value of practical science, since as Ofsted (2021) point out 'Practical work … forms a fundamental part of learning science'.

There is not always a consistent definition of what constitutes practical science; Dillon (2008, pp. 15-25) describes a variety of definitions. For this work I will use that given by Wellington (1998, p. 12) to include such things as:

- 'teacher demonstrations;
- class practicals, with all learners on similar tasks, working in small groups;
- a circus of *'experiments'* with small groups engaged in different activities, rotating in a carousel;
- investigations, organized in one of the above two ways;
- and problem-solving activities'.

For my students following the A level curriculum, only the first two of Wellington's activities are a significant part of their current experience; this is also generally true for the VLs with which they have interacted. There is a considerable body of literature concerning the importance of practical studies in science, for example Dillon (2008) and Holman (2017). These authors have identified a range of knowledge, skills and behaviours which practical scientific activity promotes. Holman (2017) draws strongly on evidence gathered in a Rapid Evidence Review report (REA, 2017) which was 'undertaken to identify any international comparisons of practical work and studies of what makes practical work good'. I have decided to use the list given by Holman (2017) as a basis for the study, this is shown in Table 2; these points are considered in more detail in the sections which follow.

Table 2 showing the main benefits of practical science, taken form Holman (2017).

1	to teach the principles of scientific inquiry.
2	to improve understanding of theory through practical experience.
3	to teach specific practical skills, such as measurement and observation, that may be useful in future study or employment.
4	to motivate and engage students.
5	to develop higher level skills and attributes such as communication, teamwork and perseverance

Practical science and the curriculum

This section there is a more detailed discussion of Holman's (2017) values of practical science. First the concept of 'How Science Works' (HSW) is introduced. This is part of the landscape for teaching science in the English education system discussed in Chapter 1. HSW has 12 components and these have been used in the design of the A level specification these are given in Table 3. I have tried to identify these concepts in relevant areas of this thesis using the **HSW** labelling given in Table 3. The following sections address each of Holman's (2017) points in turn.

Table 3 How Science Works (HSW) statements from the OCR (2021) A level chemistry specification, the HSW labels are used in the text

HSW1 Use theories, models and ideas to develop scientific explanations

HSW2 Use knowledge and understanding to pose scientific questions, define scientific problems, present scientific arguments and scientific ideas

HSW3 Use appropriate methodology, including information and communication technology (ICT), to answer scientific questions and solve scientific problems

HSW4 Carry out experimental and investigative activities, including appropriate risk management, in a range of contexts

HSW5 Analyse and interpret data to provide evidence, recognising correlations and causal relationships

HSW6 Evaluate methodology, evidence and data, and resolve conflicting evidence

HSW7 Know that scientific knowledge and understanding develops over time

HSW8 Communicate information and ideas in appropriate ways using appropriate terminology

HSW9 Consider applications and implications of science and evaluate their associated benefits and risks

HSW10 Consider ethical issues in the treatment of humans, other organisms and the environment

HSW11 Evaluate the role of the scientific community in validating new knowledge and ensuring integrity

HSW12 Evaluate the ways in which society uses science to inform decision making.

To teach the principles of scientific inquiry.

Millar (2004) suggests that practical science by ‘encouraging students to pursue their own enquiries taps into their natural curiosity. Finding things out for yourself, through your own efforts, seems natural and developmental, rather than coercive, and may also help you to remember them better. It seems to offer a way of holding up evidence, rather than authority, as the grounds for accepting knowledge.’ This is backed up by evidence from the PISA 2015 study which ‘found a positive correlation between strong epistemic knowledge about science (which roughly translates as ‘thinking scientifically’) and ‘inquiry-based instruction’’ (Holman, 2017, p. 18). From this Holman concludes that ‘doing practical science correlates with having a scientific attitude of mind’. This echoes Dewey’s (1933, p. 49) point that, ‘effective and integral thinking is possible only where the experimental method in some form is used’. In fact, Dewey (2011) considers inquiry the basis of the scientific method. However, ‘the PISA 2015 study found a negative correlation between performance on the PISA science tests and ‘inquiry-based instruction’’ (Holman, 2017, p. 18). This suggests that this type of education is in fact disruptive to the lower-level thinking skills needed to pass many ‘science tests’. Similarly, Ofsted (2021) conclude there are ‘specific challenges associated with enquiry-based teaching approaches, [including] cognitive overload, that pose ‘significant difficulties’ for novices learning science’.

For A level chemistry the learning objective, AO1, attracting around 33% of the marks, is ‘Demonstrate knowledge and understanding of scientific ideas, processes, techniques and procedures’ (OCR, 2021, p. 66). Although ‘enquiry’ is not specifically assessed, AO3, does contain to ‘Analyse, interpret and evaluate scientific information, ideas and evidence, including in relation to issues, to: … develop and refine practical design and procedures’. This does suggest that the elements of inquiry are part of the broader assessment process at A level, however, for me at least, the extent of the curriculum to be covered does not allow sufficient time for much genuine enquiry. Potentially, a VL allows for enquiry outside the constraints of the laboratory timetable. However, this requires a sophisticated package which will allow non-programmed activities, this is not possible with most applications – such as the RSC screen experiments (RSC, 2024) – but can be achieved to a limited extent with some of the PhET simulations (PhET, 2024).

To improve understanding of theory through practical experience.

Later in this chapter, I have tried to indicate that for some thinkers, such as Plato, Descartes, there is a strong distinction between mind and matter, theory and practice, whereas others such as Aristotle and Dewey, do not see the same division. Aristotle declares, ‘We consider that the architects in every profession are more estimable and know more and are wiser than the artisans, because they know the reasons of the things which are done’ (Sennett, 2009, p. 23). While Hanson (1962, p. 30) suggests ‘physical science is not just a systematic exposure of the senses to the world; it is also a way of thinking about the world, a way of forming conceptions.’ Similarly, Sennett (2009, pp. 119 - 144) discusses the concept of ‘material consciousness’. He expands this idea, talking of being ‘engaged in a continual dialogue with materials’ (ibid, p. 125) and ‘the hands-on transmission of knowledge’ (ibid, p. 57) things which are not possible in the disembodied VL.

The REA (2017) report records five studies showing a positive effect and five finding no effect of practical activities on theoretical understanding. This Holman (2017, p. 19) suggests is because, ‘performance in science tests does not correlate with practical science, but science epistemic beliefs and interest in science do. Practical science may not be the most efficient way to prepare for written tests, but it develops scientific attitudes and it builds interest in science as a career’ (ibid).

To teach specific practical skills, such as measurement and observation, that may be useful in future study or employment.

Dewey believes the main 'aim of education is to enable individuals to continue their education' (Dewey, 2011, p. 57), but that 'the mass of the pupils are never going to become scientific specialists' (ibid, p. 122). This presents a challenge in terms of deciding on the useful range of skills and 'processes used out of school' (ibid, p. 122) to teach. For my own students, studying at level 3, the majority will be continuing to higher education, often in science, so the skills developed may be of use. However, for many students the ability to carry out a titration or dissect a heart will be of no further use to them, although the skills of manual dexterity, organisation and teamwork they develop may be valuable assets.

Sennett (2009) regards the practical skills and attitudes developed in the laboratory as akin to learning a craft - 'The craftsman might also be glimpsed at a nearby laboratory' (ibid., p. 19). He develops an idea which appear similar to that of phronesis (see Chapter 3); in this, Sennett (2009, p. 6) contrasts '*Animal laborans* … the human being akin to the beast of burden' with '*Homo faber*… man as maker'. He criticises the view of Arendt (ibid., p. 7), who sees the *Animal laborans* as blinkered and focused on 'the work as an end in itself', 'fixated on the question 'How?'' while '*Homo faber* asks 'Why?'' (ibid., pp. 6-7). Suggesting rather that the craftsman does not simply focus on the product but is conscious of the purpose of their task. These are important characteristics to develop in both the real and virtual laboratories.

As discussed latter, Hanson (1962) is concerned that observation outside a theoretical framework is of limited value. He suggests (ibid., p.30) 'When language and notation are ignored in studies of observation, physics is represented as resting on sensation and low-grade experiment'. He goes further in what must be seen as critical of routine practicals and in particular, then VL, that 'the paradigm observer is not the man who sees and reports what all normal observers see and report, but the man who sees in familiar objects what no one else has seen before.'

To motivate and engage students.

Holman (2017) reviewing research studies on the motivation from practical science, concludes that, they 'provide robust evidence of a positive effect'. Going further than this Holman claims 'any science teacher will confirm that students are motivated and engaged by practical science, and this impression is backed up by the most robust evidence we have found around the impact of practical science' (ibid, p. 19). Wellcome's Science Education Tracker 2016 survey of 4,081 young people aged 14–18, schools in England, asked students about the reasons for enjoying science at school found the 'leading factors turned out to be having a good teacher and enjoying practical work'; 35% in both cases (reported in Holman, 2017, p. 19).

Sennett (2009, p. 28) identifies two types of motivation in the modern world – 'to do work for the sake of the community' or competition. However, he regards neither of these as suitable to achieve the 'craftsman's aspiration for quality'. For students' practical science activity, the motivation is unlikely to be those identified by Sennett, nor as he goes on to point out, do these really provide motivation in many situations. The work by Pink (2011) might be more relevant here, he identifies mastery, autonomy and purpose as sources of motivation. These can be seen as closer to factors which operate in a science laboratory. What needs to be avoided is what Hanson (1962, p. 30) 'described as repetitious, monotonous concatenation of spectacular sensations, and of school-laboratory experiments'. So, it is necessary for the VL to provide an engaging and motivating experience, this is often done through the process of 'gamification' (Sus et al., 2020). The addition of quizzes, competition and narrative (see for example, RSC, 2024) are also used to engage students.

To develop higher level skills and attributes such as communication, teamwork and perseverance

This is probably the area where the VL is least effective compared to the traditional school science laboratory, both teamwork and communication are social skills which are developed in interaction. It would be possible to configure student interactions (in virtual reality, such as, MIT, 2022) as part of the VL, however, I am unaware of any reported studies addressing these skills.

Constructivists emphasise the importance of learning as an interactive, social practice. They argue that learning, as well as motivation, occurs as a result of the interaction of students in the physical environment. Students appreciate time in a real laboratory (compared to VL) they 'show an appreciation of developing 'good practice for future' as they 'work as a team together', learning 'better measurement and observation skills'' (Peirson, 2020). The real laboratory creates 'a shared experience. Students arrive in the classroom with very different sets of home experiences, but an experiment creates a level playing field for discussion and reflection' (Holman, 2017, p. 18). This is very difficult to achieve in the more isolating environment of the VL.

Education and the value of practical science

Educational perspectives

There are a number are different ways to view the process of education. This section considers these with the intention to provide a framework within which to discuss the teaching of practical science, in particular, the uses of virtual laboratories. For example, Carr (1995, p. 55) identifies two main educational philosophies: traditional and liberal-progressive; these are shown in . Carr (2006) goes on to question the whole basis of educational theories, relying more on the practice of education. This in a sense mirrors the theory – practice arguments in science which form a background to this work. The VL does not fit neatly into either educational philosophy, but there are some features identified by Carr (1995), which match the VL. Both the educational slogans could be said to apply to VL: 'excellence' is preserved where students are unable to progress from one activity to the next until they have successfully completed it; while 'learning from experience' is provided in activities where students explore through problem solving tasks. In terms of organisation and curriculum, most educational VL have a fairly rigid structure (e.g. RSC, Labster) which are designed for students to perform a series of tasks and so gain specific knowledge and skills. There are others (such as some PhET activities) which allow students to explore interactions within the program in a less structured way. As there is little opportunity for group working in most VL configurations and with inevitably a fixed range of activities available, the match to the traditional method is quite strong. Conversely, the teaching methods in the VL match the progressive approach more closely. Learning is generally through 'discovery' methods with a series of activities which are intended to facilitate learning, rather than instruction. Some VLs also include assessment activities, such as multiple-choice quizzes, while others do not have any integral assessment. So, it is not really possible to fit the VL within one of these philosophies.

Table 4 showing the characteristics of traditional and liberal perspectives (from Carr, 1995)

	Traditional	Liberal progressive
Political perspective	Conservative	Liberal / communitarian
View of society	Elitist	Egalitarian
Guiding educational slogan	‘Academic excellence’	‘Learning from experience’
Canonical texts	Plato’s Republic	Rousseau’s Emile
Types of school	Grammar schools	Community schools
Classroom organization	Rigid grouping of pupils on the basis of intellectual ability	Flexible grouping of pupils on the basis of needs and interests
Curriculum content	Subject-centred: rigid subject differentiation	Child centred: weak subjective differentiation
Curriculum knowledge	Objective knowledge	Subjective knowledge
Teacher’s role	Expert, transmitting cultural heritage	Facilitator, enabling pupils to learn from personal learning
Teaching methods	Formal instruction	‘Discovery’ methods
Assessment procedures	Traditional examinations to test the acquisition of knowledge	Informal evaluations of qualitative developments in pupils understanding

Positivist

Positivists maintain that the world is as we see it and we can gain objective knowledge about it (Carr, 1995, pp. 104-107). There is an emphasis on knowledge gained from experience and a ‘deep-seated aversion to philosophical thinking’. While this perspective values the experiential nature of the VL, it would have questions about the basis of underling theories on which the VL is built.

Behaviourist

The behaviourists (e.g. Skinner, 1954; also see Gregson and Hillier, 2015, pp. 39-41) view is that experiments are performed in a structured way to demonstrate predetermined outcomes. Students learn by observing the outcomes of the experiments, repetition helps with the reinforcement of learning. For the behaviourist the VL is ideal, with predictable methodologies, results and rewards, as well as, the opportunity for multiple repetition. As Gregson and Hillier (2015, p. 40) comment ‘Some computer programs are particularly successful in reinforcing and shaping learning’. The ‘black box of the students’ minds’ (Gregson and Hillier, 2015, p. 41), mirroring the black box of the VL; the focus is on input leading to output.

Cognitive

The cognitive perspective (Ausubel, Hanesian and Novak, 1978; see Gregson and Hillier, 2015) has more questions to ask of the VL. The learner's mind is central here and how understanding is developed over time. For example, the work of Ausubel (Gregson and Hillier, 2015, p. 42) on meaningful learning requires students to reorder their cognitive structures; while the SOLO taxonomy of Biggs and Tang (2011), point to the need to include higher level activities as part of the VL. However, this perspective is perhaps more in line with the real laboratory experience, as VLs often focus on the development of practical rather than cognitive skills.

Constructivist

Constructivism has developed in several forms (Mcleod, 2024). Probably, cognitive constructivism (see Piaget, 1977) or radical constructivism (Glasersfeld, 1995) provide most appropriate tools for describing VL; while for social constructivism (Gregson and Hillier, 2015) there is an issue that the VL provides little social interaction. Considering Kolb's concept of experiential learning (Gregson and Hillier, 2015 p. 47) the VL can be accommodated as it provides a concrete experience, about which observations can be made. Similarly, the idea of situated learning within the VL can be enhanced by the use of 'game' type scenarios. For social constructivism (Gregson and Hillier, 2015 p. 48-50), the main issue is the potential lack of social interaction with most VL configurations. Although, VL embodiments can test learning throughout a planned scenario, there is no real opportunity to socially interact in most VL programs, nor are there opportunities for teamwork. Although some VL can provide scaffolded activities, there is little opportunity for individualisation of these. This is particularly an issue if we wish to work in Vygotsky's 'zone of proximal development' (Vygotsky, 1978; Gregson and Hillier, 2015, p. 49), as this would be difficult to define, using the software of which I am currently aware.

Table 5 showing a description of Bloom's Taxonomy (UArk, 2013) compared to a taxonomy for practical science in the real laboratory.

Bloom's Taxonomy (UArk,2013)		Science Taxonomy	
Knowledge	Retrieving, recognizing, and recalling relevant knowledge from long-term memory.	Evaluation	selecting relevant information from a complex situation
Understanding	Constructing meaning from oral, written, and graphic messages through interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining.	Discernment	choosing the most important factors
Applying	Carrying out or using a procedure for executing or implementing.	Experimenting	testing the relevance of a factor
Analysing	Breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing.	Analysis	assessing the relevance of those factors
Evaluating	Making judgments based on criteria and standards through checking and critiquing.	Understanding	appreciating the effect of those factors
Creating	Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing.	Knowledge	recognising the importance of a factor – a fact.

Bloom and virtual laboratories

Bloom's taxonomy (UArk, 2013) is a well-known method for analysing levels of thinking within educational environments. In the following tables I have attempted to match the level described by Bloom (as altered, UArk, 2013) with first those apparent in the real laboratory ( ) and VLs (Table 6).

Table 6 showing a description of Bloom's Taxonomy (UArk, 2013) compared to a taxonomy for virtual laboratories.

Bloom's Taxonomy (UArk, 2013)		Virtual Laboratories
Knowledge	Retrieving, recognizing, and recalling relevant knowledge from long-term memory.	basic physical laws, models, equations
Understanding	Constructing meaning from oral, written, and graphic messages through interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining.	digital form of laws, models, equations
Applying	Carrying out or using a procedure for executing or implementing.	applying models into a 'laboratory' environment
Analysing	Breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing.	producing individual results from each component model
Evaluating	Making judgments based on criteria and standards through checking and critiquing.	balancing effects from multiple interactions
Creating	Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing.	combining to produce an overall virtual environment and experience

As can be seen in Table 6, my analysis shows a close match between the levels for VL and those from Bloom (UArk, 2013). There is a general correspondence in complexity as VL and Bloom identify a hierarchy of increasing complexity though learning, mirrored in an increasing complexity of the VL structure. This shows an inductive like structure with generalisation built on parts of increasing complexity. Similarly, using an analysis based on Kolb's cycle, Caño de las Heras et al (2021) find that for the VL application they used, the VL addresses 'the lower levels of Bloom's taxonomy – knowledge, comprehension, and application. This enabled the students to build their foundational knowledge'. They continue 'As the VL progressed, the students were required to test different variables involving the other two stages of Kolb's experiential cycle of making conclusions and applying these with further experimentation, involving the higher-level skills in Bloom's taxonomy – analysis, synthesis, and evaluation' (Caño de las Heras et al, 2021). This agrees with the analysis set out in Table 6, showing the VL as scaffolding lower-level cognitive skills, increasing towards higher-level skills and mirroring Bloom's taxonomy.

However, I would suggest the structure for science, in particular practical science, is very different. As shown in , the cognitive processes for scientific understanding are often deductive going from a complicated reality and identifying features, structures and patterns in the observed data (this is discussed further in Chapter 3). This suggests there is a mismatch between the cognitive demands of science and the educational structure on which much teaching is predicated.

Since, the VL is developed using inductive principles – assuming a uniformity of nature (Okasha, 2016) in an environment created in mathematical space; learners experience a world which (in principle, at least) is developed from a construction, built from lower order thinking, to form a whole environment. Educationally, this may seem better suited to learning, as tasks can be scaffolded up through the range of cognitive skills. However, this risks losing the 'discovery', uncertainty and 'edginess' of an interaction with real materials, which exist in a 'liminal zone between problem solving and problem finding' (Sennett, 2009, p 48) – a space where real discovery can be made.

Signature Pedagogies

A useful educational perspective has been developed by Shulman (2005). He identifies a number of specific educational techniques which are particular to different disciplines. For example, for medical training, the 'ward round' is a particular feature in the education process and 'case dialogue method of teaching' features strongly in law education (ibid). For science, particularly chemistry, practical experiments are a significant feature of the education process. For a colleague, carrying out a practical 'titration and an organic synthesis' (Jackson, 2022) are essential parts of learning to be an A level chemistry student.

Looking in more detail at Shulman's (2005) method; he identifies three dimensions to signature pedagogies:-

'a surface structure, which consists of concrete, operational acts of teaching and learning, of showing and demonstrating, of questioning and answering, of interacting and with holding, of approaching and withdrawing'.

'a deep structure, a set of assumptions about how best to impart a certain body of knowledge and know-how.'

'implicit structure, a moral dimension that comprises a set of beliefs about professional attitudes, values, and dispositions.'

Applying these ideas to first practical science and then in particular to VL, draws out a number of points. Firstly, the 'surface structure' corresponds to the way that for many practicals (particularly for A level) there is a written method sheet, in my own practice, this is read through in class and understanding probed though question and answer; often I might demonstrate any novel techniques. There is a 'ritual' of donning safety glasses and lab coats – something I recall from my school days. During practicals I will circulate asking questions and helping where necessary. Sennett (2009, p. 53) suggests '[m]ost scientific laboratories are organised as workshops' where 'assistants in it undoubtedly learned from the example of their masters' (ibid, p. 74). However, he sees that 'it's harder for a scientist to pass on the capacity to look suspiciously for new problems in the course of explaining old ones or to explain the intuition formed from experience' (ibid, p.74). Perhaps this also similar to the 'ritual of case presentation, pointed questions, exploration of alternative interpretations, working diagnosis, and treatment plan' development, described by Shulman (2005, p. 54) as a 'signature pedagogy' of the hospital ward-round. A similar process occurs in many of the VL applications, with the students guided through a series of steps to carryout particular activities. For some VL e.g. Labster (2024), there is an instant help function to provide guidance and a series of questions posed during the activity.

The 'deep structure' of practical lesson is in part generated by the use of a fixed method for the activity. There are certain group of activities which need to be undertaken and skills demonstrated which constitute something akin to a canon. These are reflected in the A level examination syllabus (OCR, 2021) where 15% of the marks are gained from questions based on practical activity. This is also seen in the VL where activities such as those produced by the RSC have a particular set of activities delivered in a way recognisable to chemistry teachers.

The 'implicit structure' is reflected in the underlying attitude of teachers who value the practical and make it a central part of their practice. Again, this is particularly true for chemistry, with chemistry teachers, and eventually chemistry students, obsessing about the level of the meniscus or the exact match to a colour change. This is also reflected in the RSC activity where exact measurements are required in measuring virtual volumes. These ideas suggest the nature of some sort of club, with accepted rules, initiation procedures, and a creed based on "the scientific method". Dewey (2011, p. 122) expressed this idea, saying 'there is sometimes a ritual of laboratory instruction as well as of heathen religion'. This also chimes with Kuhn's concept of the accepted paradigm to which scientists adhere when undertaking 'normal science' (Kuhn, 1996).

In conclusion, the science practical appears to have the features of one of Shulman's signature pedagogies, showing all three types of structure. The VL equivalent shows most of these features, but it seems harder to argue the presence of an implicit structure as the transmission of 'a set of beliefs about professional attitudes, values, and dispositions' (Shulman, 2005). This I feel requires a more personal interaction, similar to the concept of phronesis (discussed in Chapter 3), where the transmission of the values requires a deeper engagement than that provided by the VL.

The Nature of Science

What constitutes science is a matter of some discussion, which is by no means settled. O'Hear (1990, p 50) suggests for some science is limited to a 'discovery of natural kinds of things' and far-reaching regularities. While, for others, science is 'about the discovery of the essences of things and of physical or causal necessities' (ibid, p. 50). Bacon provides what might be considered the 'stereotypical view' of science – 'the objective observer who frees men from the illusions and myths of the past' (ibid, p. 14), then uses observations to build knowledge. Dewey (2011, p. 121) also talks of 'observation, reflection and testing' to discover the 'dependencies of the various facts upon one another'. However, this is not the view which is now held by many of those who have thought deeply about the nature of science (for example: Hanson, 1962; Kuhn, 1996; Lakatos, 1984; Popper, 2002; Feyerabend, 2010). Recent studies in the nature of science (NOS) have focussed on two different approaches for classification. These are the consensus and family resemblance approaches, which are considered further, below.

In order to explore the nature of science we need to also understand what ideas inform the concepts of reality, truth and knowledge. These are just as contentious and are the area of study addressed by philosophers. In the hope of developing an informed view I have read texts in the area of the philosophy of science (e.g. O'Hear, 1990; Okasha, 2016; Kuhn, 1996; Popper, 2002; Redman, 1993; Feyerabend, 2010; Bird, 1998; Russell, 2000). The concepts of reality and truth are very much part of any experience in a VL, which by its nature is 'not real'. Can knowledge, then, be learnt in such an environment? I have therefore explored a small area of the vast literature devoted to the nature of reality and truth.

As Erduran and Dagher (2014, p. 3) have pointed out the 'Nature of science (NOS) has become a predominant area of research in science education'. The International History, Philosophy, and Science Teaching Group (2025) is an organisation focused on the application of history, philosophy and sociology, for the enhancement of science education. Much of the recent work on the nature of science, particularly in the field of education has been published in the group's journal, Science and Education (2025). Much of the recent literature focusses on the teaching of NOS, Matthews (2014, 2018) has edited significant collections of work in this field. Some of this work is relevant to this study and brief details are given in the sections which follow.

Demarcation

When considering the nature of science one question which arises is that of the extent of science. Most people, including the government (DfE, 2015) and exam boards (OCR, 2021) accept that the disciplines of biology, chemistry and physics are sciences. Beyond this there are often disputes for example Kemmis (in Carr, 1995, pp. 3-16) talks of political science, social science and educational science.

Popper is quite clear, that for him, the possibility of 'falsification of a system is to be taken as a criterion of demarcation' (Popper, 2002, p. 18). Lakatos (1981, 1984), on the other hand, focuses on the 'research programme' as the fundamental component and develops the ideas of Popper in relation to this larger entity. Popper (2002) would exclude those "sciences" outside the natural science, whose theories could not be tested rigorously against the possibility of falsification. Contrastingly, Kuhn (1996) sees science as an activity carried out by scientists within a paradigm. Thus, it is essentially the collective view of the scientific community which establishes what science is at any particular time. This is similar to the view of Polanyi (Redman, 1993), who sees the nature of scientific knowledge to be held in part in the 'tacit' knowledge of individual scientists.

This is a contentious field with significant disagreement between authors (see for example, Carr, 1995, pp. 96-98; Popper, 2002; Russell, 2000; Redman, 1993) as to the areas of study which can be described as science. For the purposes of this study, which is concerned with virtual laboratories in education, I will confine the term science to the traditional – biology, chemistry and physics – encountered in an FE environment. More recently debate has focused on two conceptualisations of the nature of science, focusing on what science is – rather than what science is not and these are discussed in the next two sections.

The Consensus Approach

Kuhn (1977, pp. 321- 322) identifies five, non-exhaustive, 'characteristics of a good scientific theory': accurate; consistent (internally and 'with other currently accepted theories'); broad scope; simple; and fruitful. He recognises that similar criteria could have been chosen but suggests these 'provide *the* shared basis for theory choice' (ibid, p. 322). For example, Irzik and Nola (2023, p. 1240), point out that 'some values prized by others are missing from Kuhn's list, such as inductive support by evidence and explanatory power'. The generation of a comprehensive list scientific properties or 'exclusive characteristics of science' (Kampourakis, 2016, p. 674) has been recognised as an unachievable goal (Irzik and Nola, 2023). While, Allchin (2011) cautions science 'cannot be fully or adequately expressed by a list of explicit tenets'. Consequently, much of the literature published over the last 30 years has focused on the "consensus" approach to the nature of science (NOS), see for example:- Kampourakis (2016); Lederman and Lederman (2019) and McComas (2020). This approach recognises that there are some core aspects of science which most can agree on, which in essence is a list of characteristics associated with science (in the absence of a list of necessary and sufficient conditions) thus, using 'these adjectives as descriptors of science' (Kampourakis, 2016, p. 673).

Focusing on education, McComas (2020, p. 23) suggests that NOS 'is the somewhat informal process by which recommendations have been offered and accepted by the science education community in that they are often found in science standards documents, textbooks and featured in science classrooms'. Kampourakis (2016), prefers the term '"general aspects" conceptualization' to "consensus". He claims the approach 'is an excellent and effective, as empirical research suggests, entry point to teaching about NOS'. Usefully, Kampourakis (2016) provides a table of areas of apparent agreement between a number of researchers in the field on the constituents of the NOS. From this he summarises that 'the empirical basis of scientific knowledge, its tentativeness, the role of creativity of scientists, and the diversity of views among them are important aspects of NOS' and that in teaching it is necessary 'to challenge … preconceptions, according to which scientists are always objective, work using the "scientific method," and their conclusions should be considered as truths that will not be subject to change' (ibid). McComas (2020, p. 33) suggest that 'we really do know what main NOS topics should be included in science class'.

Moreover, the aim of many supporters of this view is educational, as McComas (2020, p. 24) says, when considering 'the purpose of science instruction itself as introductory experiences in schools and higher education settings. Learners may or may not study science later at some more advanced level so what we teach in terms of both traditional science content and NOS must reflect this reality. Perhaps some of our students will become scientists or even philosophers of science, but most will not. However, all students will – we expect – become contributing members of society, consumers of products and information, *and* voters'. This is a pragmatic approach which is defended, largely on the grounds of utility, by 'empirical evidence suggesting that this conceptualization is quite effective in teaching and learning about NOS' (Kampourakis, 2016).

The consensus conceptualisation of the NOS focuses on two aspects of NOS: the nature of scientific knowledge (NOSK) and scientific enquiry (SI). Both of these are seen as important in school-based education. Lederman and Lederman (2019) suggest 'we must consider what "definition of NOSK is most developmentally appropriate and understandable'. The authors suggest this has three parts:- 'science is a body of knowledge'; 'how the knowledge is developed' and 'answering the question of "what is science?"' (ibid). They suggest the focus of teaching should be on the 'the developmental appropriateness and reasonableness of what we ask our students to learn' (ibid). This is essentially an inductive approach (see Chapter 3) viewing the NOSK as a construction of characteristics which form a body of knowledge. The authors are not concerned with an 'attempt to demarcate science from non-science', only with 'the question, "What is science?"' (ibid).

The consensus values, although not a settled list, have the general characteristics shown in Table 7 showing the consensus or "General Aspects" conceptualization of NOS, taken from Kampourakis (2016). The table shows the seven aspects of the NOSK, which many science educators would regard as elements appropriate to teach in secondary schools; Lederman and Lederman (2019) claim 'there are volumes of empirical research that indicate what students can reasonably learn and how NOSK can be effectively taught'. There are also shown a list of the aspects which are appropriate to SI, although this aspect has been less well studied within the consensus approach.

Table 7 showing the consensus or "General Aspects" conceptualization of NOS, taken from Kampourakis (2016).

Aspects of nature of scientific knowledge (NOSK)	**Aspects of scientific inquiry (SI)**
(1) Observation and inference are different.	(1) Scientific investigations all begin with a question, but do not necessarily test a hypothesis.
(2) Scientific laws and theories are distinct forms of knowledge.	(2) There is no single set and sequence of steps followed in all scientific investigations (i.e., no single scientific method).
(3) Scientific knowledge is empirical, as it is based on and/or derived from observations of the natural world.	(3) Inquiry procedures are guided by the question asked.
(4) Scientific knowledge involves human imagination and creativity.	(4) All scientists performing the same procedures might not get the same results.
(5) Scientific knowledge is subjective.	(5) Inquiry procedures can influence the results.
(6) Scientific knowledge is influenced by the cultural contexts in which it is developed	(6) Research conclusions must be consistent with the data
(7) Scientific knowledge is never absolute or certain but tentative and subject to change.	(7) Scientific data are not the same as scientific evidence.
	(8) Explanations are developed from a combination of collected data and what is already known.

The consensus approach applied to VL

It is useful to consider how the concept of the VL sits within this conceptualisation of the NOS. This is not clear cut as the VL can have different manifestations, with varying degrees of sophistication which will alter its scientific characteristics. For the purpose of illustration I am considering the VL to be a purely educational tool, which has characteristics similar the RSC titration experiments described in Chapter 3. That is a screen based VL which involved learners progressing through a series of predetermined tasks within a defined scenario, limiting progression to a fairly linear route through definite steps. Table 8 shows how the VL fits within the consensus view of the NOSK. The analysis suggests that much of the "science" involved occurs at the level of the creator of the VL, so the user does not experience the full range of aspects of NOSK. This might also be argued is the case for real school practical work where the task is highly constrained to steps on a method sheet.

Table 8 showing the application of the consensus or "General Aspects" conceptualization of NOSK to VLs, adapted from Kampourakis (2016).

Aspects of nature of scientific knowledge (NOSK)	**Aspects of nature of scientific knowledge (NOSK) applied to VLs**
(1) Observation and inference are different.	Observations in the VL are tied to the theoretical structure of the VL so are implicitly linked to inferences already made.
(2) Scientific laws and theories are distinct forms of knowledge.	Scientific laws and theories are treated in the same way once incorporated into the VL.
(3) Scientific knowledge is empirical, as it is based on and/or derived from observations of the natural world.	While the basis of scientific knowledge may be empirical, that used in the VL is in the form of theories and fixed rules.
(4) Scientific knowledge involves human imagination and creativity.	The creation of the VL uses imagination and creativity, but this is greatly circumscribed for the user.
(5) Scientific knowledge is subjective.	Scientific knowledge may be subjective for the creator but is presented as objective to the user.
(6) Scientific knowledge is influenced by the cultural contexts in which it is developed.	The VL is created in a definite cultural context, this may be different to that of the user.
(7) Scientific knowledge is never absolute or certain but tentative and subject to change.	The VL is a certain crystallisation of scientific knowledge so is not subject to change.

Table 9 showing the application of the consensus or "General Aspects" conceptualization of SI to VLs, adapted from Kampourakis (2016).

Aspects of scientific inquiry (SI)	**Aspects of nature of scientific inquiry (SI) applied to VLs**
(1) Scientific investigations all begin with a question, but do not necessarily test a hypothesis.	Inquiry using an educational VL does not test a hypothesis, the outcome is determined.
(2) There is no single set and sequence of steps followed in all scientific investigations (i.e., no single scientific method).	The set of steps in the VL is often fully defined with progress allowed only via one route.
(3) Inquiry procedures are guided by the question asked.	The inquiry is controlled by the programming of the VL.
(4) All scientists performing the same procedures might not get the same results.	The VL is designed to give consistent and reproducible results.
(5) Inquiry procedures can influence the results.	The procedures are fixed and the outcome predetermined.
(6) Research conclusions must be consistent with the data	The structure of VL ensures that the conclusions are consistent with the data
(7) Scientific data are not the same as scientific evidence.	Due to the link between the data produced and the underlying theory, there is only evidence to support that theory.
(8) Explanations are developed from a combination of collected data and what is already known.	For the VL the data is generated from the theoretical model, which incorporates the explanation.

Considering the case of SI in the VL, as shown in Table 9, there is even less science going on, for the user. A VL such as the RSC titration experiment, although giving the appearance of an investigation, provides very little scope for SI by the user. Other VL configurations (e.g. Beyond Labz, 2024) can provide more options for users and so provide a closer experience to SI, but the aspect 1, 4, 6, 7 and 8 of Table 9, are unlikely to be adequately included.

In summary, the consensus approach provides a pragmatic structure for the teaching the NOS, which is based on an educational rather than philosophical framework. Applying this approach to VLs, suggests that the end user will have a limited experience of the concepts of the NOS.

The Family Resemblance Approach

The consensus approach has been criticised for its narrow view of science (see for example, Irzik and Nola, 2011, 2014, 2023). Duschl (2008, p. 286) found when reviewing science education that 'What we have learned in the science studies as well as in the learning sciences is that a consideration only for the endpoints of generation and justification is not the proper scientific game nor is it the appropriate game of science education. What research suggests is the proper game for understanding the nature and development of scientific knowledge is engagement with the ongoing pursuit and refinement of methods, evidence, and explanations and the subsequent handing of anomalies that are a critical component of proposing and evaluating scientific models and theories. In other words, dialogical processes characterize science-in-the making approaches and the epistemic and social dynamics that seek to fill in the details between the initial and important context of generation scientific activities and the concluding and necessary context of justification activities'. He proposed an approach based on 'three integrated domains: the conceptual structures and cognitive processes used when reasoning scientifically, the epistemic frameworks used when developing and evaluating scientific knowledge, and the social processes and contexts' (Duschl, 2008, p. 277).

One approach to including a wider view of the scientific enterprise is provided by the family resemblance approach (FRA). This is based on the philosophical description by Wittgenstein of "natural families" and has been developed by the philosophers Irzik and Nola (2011, 2014). The method recognises that in many cases it is not possible to provide a list of necessary and sufficient characteristics which define a category. Irzik and Nola (2011, 2014, 2023) suggest that science is just such a case and that it is fruitless to use a list or prescriptive description. Instead, they suggest that science is made up of various diverse disciplines (e.g. astronomy, particle physics, earthquake science, medicine). These different types of endeavour are part of a wider family described as "science". Each will have different characteristics which will differ from other members but have sufficient in common to be recognised as members of the same family. Irzik and Nola (2011) suggest four broad areas which make up science: Activities (Practices, Processes of Inquiry); Aims and Values; Methodologies and Methodological rules; Products (Scientific Knowledge). The FRA suggests that these are expressed as broad categories with flexible boundaries but providing some sort of common experience of science.

Erduran and Dagher (2014) (and Dagher and Erduran, 2016, 2023) in a series of publications have developed the FRA further, in particular, applying the ideas to scientific education. These authors say 'In a nutshell, FRA recognizes that all branches of the natural sciences have shared features that distinguish them from other fields. While the shared features are not fixed, they provide enough resemblance to view these fields as scientific. The FRA can serve multiple purposes, for example, for demarcation to distinguish science from non-science or pseudoscience. However, a key purpose for applying it to science education concerns the potential of its aspects to support reasoning meaningfully about science in disciplinary and societal contexts. FRA accounts for the cognitive, epistemic, institutional, and social aspects of scientific knowledge' (Dagher and Erduran, 2023). (The term Reconceptualised Family Resemblance is also used in the literature to distinguish it from the general philosophical applications of FRA.) The development of this method can be seen through the work of Irzik and Nola, Erduran and Dagher (some of which has already been cited), Matthews (2014, 2018) and publications in Science and Education (2025). Several practical studies have been undertaken into the implementation of the FRA in schools, for example the recent Project Calibrate, which is discussed in more detail below.

Theoretical Model for the FRA

The application of the FRA to the NOS has been largely based on the philosophical development by Idzik and Nola (2011, 2014, 2023). Although this development is some interest, for the purposes of this thesis I will concentrate on the most recent paper (2023) as representing the FRA. Idzik and Nola (2023, p. 1228) suggest that the FRA should be viewed as standing on three pillars. 'The first pillar is a distinction between science as a cognitive-epistemic system and science as a social institution. The second pillar is a set of science categories and characteristics that give substance to this distinction. The third pillar is that different scientific disciplines form a family resemblance'.

The inclusion of social factors contrasts with the consensus approach which focuses on science as a cognitive-epistemic exercise. The FRA leads to a much wider consideration of the NOS within the context of a particular society at a particular time. The second pillar has been expanded over time from eight (Idzik and Nola, 2011) to twelve (Idzik and Nola, 2023) categories, these are given in Table 10. The authors note these are of an 'open-ended nature' (ibid, p. 1234) and so subject to change.

Table 10 showing the categories of the FRA to NOS (from Idzik and Nola, 2023).

Science as cognitive- epistemic system	
Cat 1	Practices of inquiry
Cat 2	Aims and epistemic values
Cat 3	Methods and methodological rules
Cat 4	Scientific knowledge or belief
Science as Social-Institutional System	
Cat 5	Professional activities
Cat 6	Scientific ethos
Cat 7	Social certification and dissemination of items in cat 4
Cat 8	Non-epistemic social values
Cat 9	Reward structure
Cat 10	Social Organization
Cat 11	Power structure
Cat 12	Economics of science

The third pillar develops the idea that rather than a strict list of attributes 'sciences are similar to one another constituting a family resemblance' (ibid, p. 1231). This approach recognises that for a broad concept such as the NOS there are many factors can be considered relevant. Irzik and Nola (2023, p. 1232) describe the diverse examples of astronomy, particle physics, earthquake science and medicine, which are all regarded as sciences, but do not have a consistent set of properties in common. While all have the collection of data and the making of inference in common, particle physics and medicine employ experimental methods, however, astronomy and earthquake science do not. Similarly, medicine uses randomised controlled trials, while the other three use hypothetico-deductive testing. The FRA then suggest that ‘they partially overlap, like the members of closely related extended family. In short, taken altogether, they form a family resemblance’ (ibid, p. 1232).

Practical Application

Erduran and co-workers have carried out extensive studies of the application of FRA to science education within the English school system. Some of this work has been undertaken as part of Project Calibrate (2025) resulting in a series of publications, including Cullinane, Erduran and Wooding (2019); Erduran, Ioannidou and Baird (2021) and Erduran (2021). The aim of the project was to investigate and improve students experiences of practical science. In particular, the disjoint between ‘fairly simplistic account of the scientific method’ and ‘how scientists actually *do* science’ (Erduran, 2021). By working with a wide range of stakeholders, including students, the project aimed to improve practical science teaching by showing the wide range of methods used and that ‘there is no one single method but rather a diversity of scientific methods’ (Erduran, 2021). One of the key features of the approach used is the focus on Brandon’s matrix (1994) as a way of illustrating and classifying the range of scientific methods (see Chapter 1). Two papers from the project are particularly relevant to this study and are briefly reviewed next.

The paper by Cullinane, Erduran and Wooding (2019) reports on the investigation of the assessment of practical science in GCSE chemistry exams. The authors used Brandon’s matrix (1994) to characterise the extent of hypothetical testing and manipulation evident in exam questions. They found that despite the expectation that the hypothetical-deductive model is the basis of the “scientific method”, the emphasis in exam questions did not support this. In fact, it was shown that ‘manipulative parameter measurement dominated the exam papers’ (ibid). This is particularly relevant as for exam based subjects there is a tendency ‘to teach to the test’ (ibid) and so it is vital to design ‘*tests worth teaching to*’ (Erduran, 2021).

The study reported by Erduran, Ioannidou and Baird (2021) shows one method of introducing a more holistic approach to the teaching of the NOS. Based on the framework provided by Brandon’s matrix (1994), the authors developed video lessons demonstrating a wider variety of scientific activities. By emphasising data gathering outside the hypothetical-deductive testing model, students are shown to gain a greater understanding of practical science.

A recent paper by Shi (2023) describes in some detail a course, based on the principles of the FRA, delivered to Chinese senior high school students. Although the sample size was small (14) there was a similar sized control group, both of 17-year-old students. The results clearly show an improved recognition of the experimental group in the connection between science, technology and society. Demonstrating that the FRA ‘provided a clear teaching framework for high school’ (ibid) philosophy of science courses and the value of explicitly teaching the philosophy of science.

The FRA applied to VL

Here two aspects of the application of the FRA to VLs are considered. Firstly, the approach can be used to address the question posed in Chapter 1 – *What makes a laboratory?* and in particular, a VL. By adopting an FRA we can try to identify a range of characteristics which might form the basis of family resemblances, a suggested range is given in Table 11, for a scientific laboratory. While Table 12 shows a similar list for VLs. Note that these are intended to purely indicative of the type of categories which might be used in an FRA analysis; a fuller analysis is beyond the scope of this thesis.

Table 11 showing a possible set of characteristics for identifying a scientific laboratory within the FRA

A space and time dedicated to scientific activity
A dedicated school / college / university laboratory
A site where observation/recordings of data are made
A place for practical investigation of scientific theories
A place for constructing and testing scientific equipment
A place for the analysis of biological, chemical or physical samples

Table 12 showing a possible set of characteristics for identifying a VL within the FRA

A digital environment for scientific activity
A computer program designed to simulate a scientific experiment
A video recording of a scientific experiment
An animation of a scientific experiment
A computer game with scientific content
A computer program intended to mimic behaviour of biological, chemical or physical samples
An augmented reality program with scientific features
A virtual reality environment to mimic a science laboratory

Table 13 showing a comparison of a VL, using the example of the RSC titration experiment discussed in this work, to the FRA criteria from Irzik and Nola (2023)

Science as cognitive- epistemic system	Relation to a VL (e.g. RSC titration)
Cat 1 Practices of inquiry	Not really available to the user
Cat 2 Aims and epistemic values	Set implicitly in the scenario
Cat 3 Methods and methodological rules	Defined by the structure of the VL
Cat 4 Scientific knowledge or belief	Transferred explicitly by the VL
Science as Social-Institutional System	
Cat 5 Professional activities	Scientists as part of the response to a potential disaster
Cat 6 Scientific ethos	Addressed through protecting the SSSI environment. Also, the necessity of the correct procedure to obtain the reliable values
Cat 7 Social certification and dissemination of items in cat 4	This is external to the VL and it is the prestige of the RSC which validates the VL
Cat 8 Non-epistemic social values	Addressed through protecting the environment
Cat 9 Reward structure	Gamified activity rewards "success" with a points structure
Cat 10 Social Organization	Implicit in the "scientists take charge" scenario
Cat 11 Power structure	Implicit in the authoritative voice of Dr Patel, the VL guide
Cat 12 Economics of science	Implicit in the potential cost of decontamination for a chemical spillage

Secondly, the FRA can be used to categorise VL as a scientific activity. As indicated in Table 8 and Table 9 the VL does not meet all the criteria for the for the consensus approach to NOSK or SI. Table 13 shows an example to applying the FRA to a specific VL, that of the RSC titration experiment described in Chapter 3. Looking at categories 1 – 4, suggests that the science which exists is external to the user, what they experience as science is mediated through the VL. The "science" is done elsewhere and the NOS is particular to the VL, there is no real "reality check". Categories 5 – 8, 10 – 12, show perhaps even more externalisation of the science with each aspect of the users experience in the VL being part of an external story. Only Cat 9, the reward system, directly impacts the users with a gamified points system, here the actions of the learner can have a direct influence.

So, in summary, VL can be viewed through the perspectives of Popper's falsification, the consensus and FRA to NOS. Each of these views suggest that VLs, constituted in simple screen experiments, such as the RSC titration experiments, seems to lack many of the characteristic of science. What the students experience is not the NOS which is suggested by these perspectives.

The nature of reality

The nature of reality has been the subject of debate for thousands of years. It is probably one of the defining questions of human existence. The extent to which we can trust our senses to give an 'objective' view of the world around us is probably a question implicit in every judgement we make. When we start to look at science as way of finding out about the world, we need to consider how we can know what is real. The area of philosophy concerned with the nature of reality is known as ontology. The detail of this subject is well beyond the scope of this thesis; however, in Chapter 3, I discuss how this bears on the methodology for this study, while here I am taking a very narrow view of how science investigates reality. In particular, the verisimilitude of experience in both real and virtual laboratories, and how this relates to the idea of an 'objective reality'.

Much of the study of ontology can be traced back to ancient Greece. Russell (2000, p. 122) asserts that 'Plato and Aristotle were the most influential of all philosophers, ancient, medieval, or modern; and of the two, it was Plato who had the greater effect upon subsequent ages'. Although Russell is critical of Plato, particularly his political ideas, he acknowledges the importance of his work.

Plato's views of reality are set out within his most significant work 'The Republic' (Plato, 1987). These are derived from the idea of Parmenides that 'reality is eternal and timeless, and that, on logical grounds, all change must be illusory'; and that, of Heraclitus that 'there is nothing permanent in the sensible world' (Russell, 2000, p. 123). These inconsistent ideas lead Plato to conclude that 'knowledge is not to be derived from the senses, but is only achieved by the intellect' (Russell, 2000, p. 123; also see the ideas of Hanson, below). Plato is concerned with 'the distinction between reality and appearance' (Russell, 2000, p. 135). This leads to the conclusion that knowledge 'is of something that exits, for what does not exist is nothing', knowledge is of 'a super-sensible eternal world'; while opinion is 'the world presented to the senses' (Russell, 2000, p. 136). This is summed up in the quote 'But those who see the absolute and eternal and immutable may be said to know, and not to have opinion only' (Russell, 2000, p. 136). This leads to the theory of ideas, in which gives that there are general words which express a category or type. Russell (2000) illustrates this with reference to *the cat*, as a general term of language, rather than any specific cat. Any particular cat is mortal but cats in general are 'eternal'. There is a further metaphysical argument that 'the cat', an ideal cat, has been created by God, particular cats more or less imperfectly have the nature of cat. This leads to the idea that '*the* cat is real; particular cats are only apparent' (Russell, 2000, p. 137). Plato is distinguishing between the intellect, leading to ‘reason’ and ‘understanding’; and sense-perception. Russell (2000, p. 143) is critical of this distinction between the real and apparent, and he argues on logical grounds that ‘if appearance really appears, it is not nothing, and is therefore part of reality’ while ‘if appearance does not really appears, why trouble our heads about it?’ concluding that ‘ any attempt to divide the world into portions of which one is more ‘real’ than the other, is doomed to failure’. Ultimately, Plato’s views, based on those of Socrates, are that ‘the body is an hinderance in the acquisition of knowledge, and that sight and hearing are inaccurate witnesses: true existence, if revealed to the soul at all, is revealed in thought, not in sense’ Russell (2000, p. 150). This is a total rejection of empirical methods; producing a reliance on mathematics and mystic insight as the only means of determining reality. This is very much at odds with the views of many scientists who follow much closer to Bacon’s view of measurement without presupposition (O’Hear, 1990). Perhaps the view of Hanson (1962, p. 30) can help with this dilemma – ‘physical science is not just a systematic exposure of the senses to the world; it is also a way of thinking about the world, a way of forming conceptions’.

One of the most important ideas proposed by Plato (1987), within ‘The Republic’, is the ‘Allegory of cave’ (see Russell, 2000, pp. 140-141; Kenny, 1997, p. 25). This story describes prisoners held in a cave. The prisoners are chained so that they can only see one wall. On this wall, shadows from passing travellers and the outside world, are seen. This is all the experience of the world, and each other, that the prisoners have: this is their reality. One day, one of the prisoners is able to escape and see the world outside the cave. He returns to the cave to explain to his brother prisoners that what they have seen in the past, is only a projection of reality. The prisoners who have not seen the outside world are incredulous. Plato likens this to the problem faced by the philosopher who tries to describe a deeper understanding of the world to a sceptical population and because he has seen the world in sunlight, he is no longer able to see the shapes of the shadows as clearly as before.

This has a clear link to the concept of the VL which might be equated to that limited experience of the prisoners in the cave. The prisoners in the cave experience the 2-dimensional world projected on the wall, much as, in the same way most VL applications portray a 3-dimensional world on a 2-dimensional screen. In the cave, 2-dimensional shadows of the world give a heightened consciousness of form, demarcation and movement; qualities such as colour, texture and depth are completely absent – they are unknown-unknowns. The same problem may arise with the VL where the participant is unaware of the factors which are relevant to a 3-dimensional interaction in the laboratory – seeing a 2-dimensional representation as the ‘real’ thing. The designer of the VL will almost certainly have experienced the ‘real’ laboratory before designing the virtual one, how else could they hope to represent it? They will therefore be as the returning prisoner – trying to explain the unimaginable with an insufficient vocabulary. To the designer, the VL will have the qualities held in their tacit understanding developed in the real laboratory. They will see the VL through the lens of their experience of the real laboratory. However, the participants in the VL will have a different experience if they have not already seen the ‘real’ experiment. The designer, like the prisoner returning to the cave, needs to describe something beyond the experience and comprehension of the participants.

Other philosophers have presented alternative interpretations, for example, Zeno, founder of Stoicism, advocates a ‘solid’ materialistic view of reality (Russell, 2000, p. 261). He views the Universe as deterministic following the natural laws. This view reflects both positively and negatively on the concept of the VL. The VL depends on the Universe being deterministic, without which we run into problems with causality and induction discussed below. Moreover, the very concept of a VL is predicated on the ability to predict the future from a known starting point. This is a Cartesian view (Russell, 2000, p. 551) supported by Hobbes (ibid, p. 299). The concept of Laplace’s ‘deductive chain’ (Hanson, 1962, p. 51) of calculation in the real world, is an essential underpinning of the VL. This is a mechanistic view of the Universe, as the Newtonian analogy of the mechanical watch (Wiki, 2021), which gives credence to the calculated world of the VL. If, as Laplace claims the whole Universe can be calculated following known laws, then, given sufficient knowledge, the VL can replicate anything. Dawkins (1991), while accepting the analogy of the watch, questions the metaphysical assumption that the watch must have a maker. He believes the underlying processes are purely random, disputing the analogy of Paley that a 'watch must have had a maker' (ibid, p. 4). However, the concept of the VL raises issues in relation to Zeno's solid materialism. The VL is a representation of reality it does not give the user a true picture of what is really happening (the movement of electrons and photons) but an edited perspective of another process. The processes which happen may be perceived by the user as real, but do not have a solid materialistic existence.

In order to discuss the work presented in this thesis there needs to be some basis of agreement about how the Universe is observed (discussed in more detail below). O'Hear (1990, p.130) maintains that 'the contemporary philosopher of science…is likely to accept the world and its inhabitants as a starting point' and 'that there is a world independent of those who observe it'. I will generally, be accepting this as a starting point, dismissing 'Cartesian doubt' (Russell, 2000, p. 547; O'Hear, 1990, p. 130), to avoid being lost in a spiral of virtual realities. In accepting that the world is largely as we perceive it, for a VL there is a need to mirror this. For instance, in order to carry out calculations we need to know how things interact. For a manageable calculation we need to take Roscelin's view that reality as made up from parts, rather than existing as the whole (Russell, 2000, p. 428). This agrees with Democritus who saw truth as 'only 'atoms and voids'' (Kenny, 1997, p. 12) and is contrary to the concept of Gestalt (Wertheimer, 1923). Hegel (see Russell, 2000, p. 703) has a view which might be considered as a precursor of Gestalt, in that he views reality as a self-consistent whole, which is a complex system, and cannot be regarded in terms of its parts. Russell (2000, p. 703) sums up Hegel view as saying 'that nothing can be really true unless it is about Reality as a whole'. This cause issues for VL as if reality can only be perceived as a whole then it makes little sense to model small parts of it.

Berkley (quoted in Russell, 2000, pp. 624-625), however, argues that 'the reality of sensible things consists in being perceived' and against 'to exist is one thing, and to be perceived is another' backing up the argument with the example of lukewarm water. If you hold your hands, separately, in hot and cold water and then put both into warm water – one hand feels hot and the other cold, yet they are the same temperature, thus 'heat and cold are only sensations existing in our minds' (Russell, 2000, p. 625). However, O'Hear (1990, p. 132) describes the view 'dominant in natural science' as that of a distinction 'between the manifest image (the world as it appears to us) and the scientific image (the world as it is in itself)'. An example of this perspective is colour vision. The sensation of colour is due to the interaction of 'colourless photons with our visual cones'. Our perception of colour is related to the frequencies of the photons, bees for example respond to ultraviolet light invisible to humans (Peitsch et al., 2004). This leads to an 'absolute conception of the world' (O'Hear, 1990, p. 133), aligned to the reductionist view of science in which biology, reduces to chemical interactions, chemistry to physical interactions and physics to the 'regular rule-governed movements of atoms in the void' (ibid). This conforms to the Newtonian view of absolute time and space but is at odds with the Gestalt philosophy discussed below.

Descartes developed the concept of dualism – 'two kinds of 'stuff': res extesa, the 'stuff' that occupies space, and res cogitans, the mental stuff' (Biesta and Burbules, 2003, p. 9); the distinction of mind and matter. Famously, he then states, '*Cogito ergo sum*', that is, 'I think, therefore, I exist' (Russell, 2000, p. 353; Kenny, 1997, p. 116; Warburton, 2001, p. 51), placing reality in the mind. The exact meaning of this, as with much of philosophy, is an area for debate (Russell, 2000, p. 20, 353, 550; Kenny, 1997, p. 116; Warburton, 2001, p. 51) as to what this truly means. Gassendi (Russell, 2000, p. 353) provides an alternative view '*ambulo ergo sum*'; I walk therefore I am. This emphasises the connection of mind and body; and action as part of the thought process. This echoes Aristotle's concept of *phronesis*; that is, ‘practical wisdom’ (Costello, 2018, Massingham, 2019; discussed further in Chapter 3) and prefigures the thoughts of Peirce and Dewey. This is in part the basis of pragmatism discussed by Sennett (2009, pp. 286-291) and Biesta and Burbules (2003, pp. 1-23). Biesta and Burbules (2003, p. 10), sum up Dewey’s idea as ‘reality only ‘reveals’ itself as a result of activities – the ‘doings’ – of the organism’. These ideas suggest that the VL could create ‘reality’ for the user through a process of active engagement.

Orwell (1961) explores the limits of the concept of reality in the novel 1984, suggesting ‘Reality exists in the human mind, and nowhere else. Not in the individual mind, which can make mistakes, and in any case soon perishes: only in the mind of the Party, which is collective and immortal.’ (Orwell, 1961, p. 205); this echoes the views of Plato that reality is in thought and is immortal. Orwell goes on to question empirical reality further when Winston Smith is subjected to torture and asked how many fingers he sees before his eyes - 'How can I help seeing what is in front of my eyes? Two and two are four’ (ibid., p. 207; see, also O’Hear, 1990, p. 130). The reply is ‘Sometimes, Winston. Sometimes they are five. Sometimes they are three. Sometimes they are all of them at once’ (Orwell, 1961, p. 207). For Winston’s reality changed before his eyes ‘somehow due to the mysterious identity between five and four.’ (Orwell, 1961, p. 208).

This power to change reality is not limited to fiction, for example the OCR A level chemistry specification states students should know ‘the precipitation reactions, including ionic equations, of the aqueous anions Cl^-, Br^- and I^- with aqueous silver ions, followed by aqueous ammonia, and their use as a test for different halide ions’ (OCR, 2021, 3.1.4 (g)). The required answer for the bromide ion is a ‘cream’ precipitate (OCR, 2014), from personal experience, and that of my students, the colour is often not cream, but off-white, beige, brown or ‘muddy’ – but none of these answers match the mark scheme, so would not gain a mark; for the A level student ‘reality’ is defined by the specification and the mark scheme. There are many other examples in life where what is seen, or allowed to be seen, is not determined by the observer, but by the context of the observation - it is for the powerful to determine the truth; as Lakatos (1984, p. 94) tells us – ‘truth lies in power’.

So, to summarise the ideas presented here, there are few who see reality as pure state. The reality which we experience is modified by our beliefs and expectations. Whether or not we accept an ‘objective reality’ our individual experience will be different from others. The reality that I experience is different from that of my students. In a sense I have been out of ‘the cave’ and am trying to describe what I have seen of the world, the nature of science, to those who have not experienced what I have. This is the case for the VL in two senses. For myself, I have experienced using VL type programs in a research environment, I have seen the limitations, I have a feeling, rightly or wrongly, for the level of trust that I can put in the VL simulation. I have seen experiments and computer-generated results compared and have a ‘feel’ for the goodness of fit. Secondly, the VL is projecting ideas and concepts which students may not have been aware of before or in a novel manner; the VL, like Plato’s prisoner is struggling to express a 3-dimensional world to those who have only a 2-dimensional experience of it.

There is a further layer for my students, they, are seeing the computer generate results, are they real for them? Are they, like the news, viewed on their phones, or social media or ‘fake news’? Their experience of technology is very different to mine. Many will have an implicit assumption about the truth or otherwise of computer-generated material. Their reality – particularly their virtual reality – maybe very different as well.

Time

The concept of time is related to that of reality and experience. When we think about our experience in a real or VL, we frame it in our own context of time. What precedes the experience and what follows it – the ordering of events. The concept of time used in this work follows the ideas of St. Augustine (Russell, 2000, p. 352) and Kant (ibid., p. 680). Augustine places all time in the present viewing the past and future though the lens of the present - 'a present of things past, a present of things present, and a present of things future' (quoted in Russell, 2000, p. 352). The ''past' must be identified with memory, and 'future' with expectation' (ibid. p. 352). Our experience of time is essentially subjective.

Time passes through the lens of the present – we all have different memories; we all have different expectation – these all emanate from the time we call the present: the point of our experience. It could be viewed as many strands passing through a hole in a card; the card ever moving along collapses all our expectations into the point of the present and then they spread out again as our memories change and fade. This is acknowledged in the law where contemporaneously recorded evidence is valued, and cases not pursued after the passage of time. This description is of a more subjective version of what may be considered as the many-worlds view of time which has emerged in physics (see for example, Cossins, 2020).

The experience of time is crucial to that of the VL. In many VL configurations it is possible to manipulate time, speeding up, slowing down stopping or even reversing processes: concertinaing millennia into seconds or stretching nanoseconds into minutes. Moreover, the control of time is often explicitly in the hands of the user. This makes the processes experienced in the VL very different to that in the real laboratory, where we are often far from being in control. Time is linked to the concept of causality, which is explored below.

Fact

When we are considering education, particularly science education, students expect to learn facts. They become frustrated when you are not sure of an answer or use weasel words – it all depends… The VL is expected to provide 'facts' – certainty. For many students the expectation is that the VL mirrors reality.

So, what are facts? If there is an objective reality then 'for 'tough-minded' philosophers, observation is just opening one's eyes and looking. Facts are simply the things that happen; hard, sheer, plain and unvarnished' (Hanson, 1962, p. 31). Russell (2000, p. 132) suggests that 'on questions of fact, we can appeal to science and scientific method' and that ''facts' are stubborn and cannot be manipulated' (ibid, p. 780). For Bacon facts are determined by observation, they are the result of careful study and an inductive process of 'reading the book of nature with fresh eyes' (O'Hear, 1990, p. 16). This is straight forward and on the surface simple, but as with the nature of reality, it rests on many untested assumptions.

For example, Hanson (1962) discusses the contribution of language to modification of facts. He points out that the form of language used affects the nature of a fact. He asserts that 'facts are not picturable, observable entities' (ibid, p. 31) and that they must be expressed in language. This leads to the idea that some facts are ''inexpressible in principle', a fact which constitutionally resists articulation'. This would be a fact which could be known but 'for which no expression was available'. This is reminiscent of the tacit knowledge proposed by Polanyi (Redman, 1993). Hanson explores the question of whether changing the form of the language alters the way a fact is expressed. Expressing the 'sun is yellow' in terms of a verb (which is the case in some languages e.g. Arabic and Russian) as 'the sun yellows' or adverbially ‘the sun glows yellowly’ exemplifies this. Does this change of language, change the fact? Hanson (1962, p. 32) quotes Wittgenstein ‘It would be possible to imagine people who, as it were, thought much more definitely than we , and used different words were we used only one’ and Kant ‘… they [who philosophize in Latin] have only two words in this connexion, while we [Germans] have three, hence they lack a concept we possess’ (Hanson, 1962, p. 33). Famously, Eskimo languages have many words for snow, depending on its qualities in a way which are not easily expressed and may not even be expressible in English (see Hanson, 1962, p. 33, n.1). However, this appears not to be the view of Russell (2000, p. 776), who, when discussing the ideas of Dewey, states ‘when you assert a sentence, you express a ‘belief’, which may be equally well expressed in a different language’. This is far from Hanson’s perspective, who considerers that language is capable of encapsulating an idea or fact beyond that shown by a picture. However, he admits there is an argument, following Wittgenstein, that ‘indicating by means of language that some things cannot be thought is a suspect procedure. Anything one can indicate in our language *is* something that can be indicated in our language’ (Hanson, 1962, p. 34).

It is apparent from these quotes and the analysis by Hanson, that the way an observation is transformed into a fact depends on the observer. Hanson is quite clear in his view that ‘facts’ depend on language, ‘Language can encapsulate scenes and sounds’ (ibid, p. 27), but ‘if a distinction cannot be made in language it cannot be made conceptually’ (ibid, p. 34). This extends to the notation used in mathematics, ideas such as the rules relating velocity, time, distance and acceleration can be expressed algebraically. For me this is the most natural way to think of and use them, but this type of language forms the framework of these relationships. It is difficult to think of acceleration expressed in this way, as the same as, the visceral thrill of the accelerating jet aircraft or fairground ride. Hanson (1962, p. 36) suggests nature of the language used might change our view of the world - ‘given the same world, it might be construed differently. We might have spoken of it, thought of it, perceived it differently.’ Crucially, this leads to the conjecture ‘perhaps facts are somehow moulded by the logical forms of the fact-stating language’ (ibid, p. 36). This point is of fundamental significance in considering the VL, which is constructed out of a computer language, conceived in a natural language, expressed in mathematical notational language. There are many stages of translation as well as conceptual barriers between and observation in the ‘real’ world and that in the VL.

The constraints of language chime with the ideas of schema for organising information proposed by Bartlett (Brewer and Nakamura, 1984). These schemata provide a structure into which new ideas can be fitted. This leads onto the concept of theory loaded or theory-ladeness (Hanson, 1962, p. 54; Kuhn, 1996; Okasha, 2016; O’Hear, 1990) which effect observations as well as the ‘construction’ of facts and the explanation of causality.

Theory-laden observation

Building on the idea that language influences how we see the world Hanson (1962, p. 19) suggests 'seeing is a 'theory-laden' undertaking'. Thinking again of when we observe an object, we can describe a physical process in which a photon of light passes from an object, enters our eyes and produces an electro-chemical change in the retina. In Hanson's example of Tycho and Kepler (ibid., pp. 5-12) observing dawn, he suggests both men are 'aware of a brilliant yellow-white disc in a blue expanse over a green one'. However, although they both detect the same photons, do they see the same thing? Hanson suggests they do not. He suggests that it is not simply a matter of '*ex post facto* interpretations' of the scene based on their different ideas of the motion of the planets – it is more fundamental. The very words they use to describe the scene have for them different meanings. If they draw the scene then the pictures would be the same – 'The sun appears to them in the same way' (ibid., p.8). However, the interpretation is part of the processing of the data, there is a framework into which the data is fitted. This idea is expanded by considering optical illusions, for example the cube shown in Figure 11.

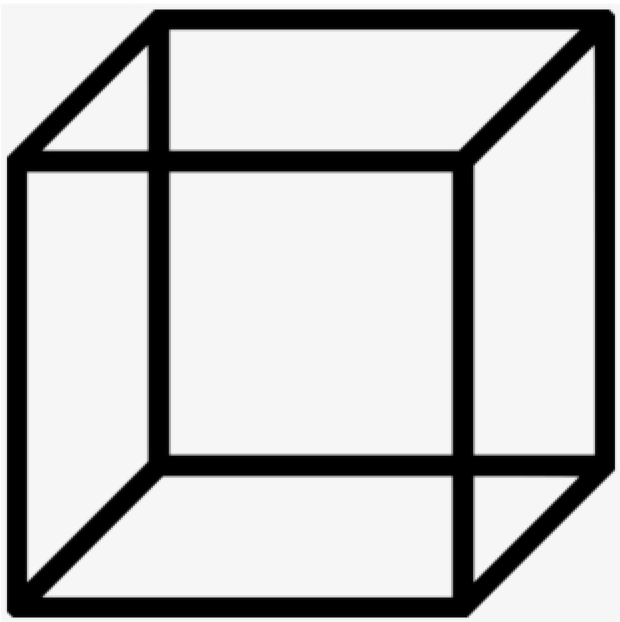

Figure 11, a 'cube' which could be viewed from above or below, or perhaps just a collection of lines. (see Hanson, 1962, p. 9 Fig.1)

Whether the box appears viewed for above or below is part of the 'seeing' process, not rationalised after viewing. Likewise, the old/young lady illusion shown in Figure 12, illustrates the Gestalt switch which happens when two images seem equally possible. In these illusions, you view the picture as one thing or the other – there is a switch between the two, but when you see the young woman – that is what you see and only when you switch views, in your mind, do you see the old woman – and then not the young one. It is very difficult – if not impossible to hold both views simultaneously. This switch considered by Wittgenstein (Warburton, 2001, p. 235) in terms of expectations; while Hanson (1962, pp. 8-24) develops these ideas to show how our observations are influenced by prior experience and the concepts we already hold. Our view of any VL will be then coloured by our experience; and we are able to make the switch between seeing the VL as a collection of lines on a screen and a laboratory in which experiments are possible.

Figure 12, showing the 'Gestalt switch' between the images of a young or old lady (see Hanson, 1962, p. 11, Fig.2).

This concept of theory-ladeness is developed by Kuhn (1996) into that of the paradigm. Kuhn views the scientist as working within a paradigm which defines how they see the world. This paradigm is developed through education, training and peer pressure to colour the way the world is seen. This is reinforced by the use of language, the meaning attached to words and ways of expressing knowledge. For example, Newton chose to express the colours of visible light as 7 distinct divisions; however, we now know that the normal eye responds to three, yet we still talk of the 7 colours of the rainbow and if we look at a rainbow this what we try to see. Another example might be the way that human's arbitrary political divisions into countries affect the way plants and animals are classified and counted.

O'Hear (1990, p. 90) accepts that 'there seems to be no way of describing objective states of affairs which are assumptionless, even at the everyday level'; but is still critical of the philosophers who 'saw no viable distinction between observation and theory, and little point in trying to draw the distinction anyway'. He specifically criticises the work of Kuhn, in which he identifies two theses, the first - a 'weak thesis…that all observations are conditioned by presuppositions, assumptions regarding similarity and dissimilarity, directions of interest, and so on' (O'Hear, 1990, p. 82, 83). This he dismisses, as this does 'not imply that precisely formulated or systematic assumptions are guiding one's observations, and is quite consistent with pretty random and undirected noticings of aspects and features of one's environment' (O'Hear, 1990, p. 83). He claims that these effects are in a sense random and not related to underlying 'theories'. This, however, does not really answer Hanson's (1962, p. 36) point that each individual interprets their observation in relation to their own particular experience and that 'perhaps facts are somehow moulded by the logical forms of the fact-stating language'.

O'Hear (1990, p. 83) then analyses Kuhn's 'strong thesis' that 'observing data in science depends crucially on the paradigm one holds' and that 'one's observations are always biased in favour of the paradigm'. This he criticises, rightly in my view, pointing out that Kuhn defends his thesis of incommensurability by describing 'the content of various paradigms in a way which presupposes the truth of none of the paradigms concerned' (ibid, p. 84). In particular, he looks at the example used by Kuhn (ibid, p. 71) of the pendulum described by Galileo. Kuhn maintains that the observation of regularity made by Galileo was enhanced by his theoretical expectation of seeing a regular pattern, in contrast to the Aristotelian view of a constrained fall. The concept of observational bias is further examined by O'Hear (1990, p. 101). He points out that 'any observational bias is going to be consistent with different stories about its underlying nature'. These stories may include 'unobservable entities and forces', (see Hesse in O'Hear, 1990, pp. 86-88). Similarly, Wittgenstein (quoted in Hanson, 1962, p. 93) maintains that 'the fact it can be described by Newtonian Mechanics tells us nothing about the world; but *this* tells us something, namely, that the world can be described in that particular way in which as a matter of fact it is described'. This suggests that for the VL it is *the reproduction of the observed form the real world* which gives validity to the process, rather than being justified by the underlying theory. Put another way, the importance of the VL is it replication of the real world, how is achieved, does not tell us anything about the underlying nature of the world. This is essentially, a positivist position, which O'Hear, (1990, p. 113) claims is 'impregnable once it is realized that conflicting explanations at the deep theoretical level can be equivalent at the level of empirical observability'.

These ideas must be a consideration in the design of the VL. Clearly the VL is based on underpinning theory from which the experience is generated. However, the way that things appear to the observer in the VL is overlaid by the theories which have been employed in its generation. This theory-ladeness then determines the experience of learners, modifying their observations and changing expectations. An example would be the simulation of an experiment to demonstrate Ohm's Law (as shown in Chapter 3). The simulations (e.g. PhET, 2024; Praxilabs, 2024) focus on the measurement of current and voltage in various configurations. Students are more or less able to reproduce an experiment from the real laboratory, generating a table of values and calculations which agree with Ohm's Law. However, the underlying assumptions determine what the student experiences. At the most obvious level Ohm's Law only applies at constant temperature, how is this expressed in the VL? Or is the effect ignored? The inclusion of a thermometer in the laboratory equipment would suggest the importance of temperature. The accuracy or otherwise of real laboratory equipment can lead to results which do not necessarily fully support the theory being tested. In the VL the underpinning theories determine what observations are possible. Thus, it is not possible to investigate an effect not imagined in the theory – the experiment is locked in a Kuhnian paradigm which determines the range of possibility.

What is observed in the VL will then depend on the sophistication of the theories used. Moreover, the observation will be constrained by the theoretical model, just as Hanson (1962, p. 36) shows language can affect the very way we think. What we see as possible depends on the theories we hold. Until Galileo saw the moons of Jupiter through a telescope, no one had observed them, even though they are visible with the naked eye (O'Hear, 1990, p. 114). Observers did not see that it was possible to see the moons – for them the moons could not exist – so they could not see them. It was only when Galileo showed clearly that there were moons, that it was possible to see a dot or smudge near Jupiter could be a moon – until then it was impossible. As Goethe (quoted in Hanson, 1962, p. 4) puts it, 'Were the eye not attuned to the Sun, The Sun could never be seen by it'.

Figure 13 showing many spots on a white background, it is possible to make out a Dalmatian dog (from 5c8f91f1a.gif (570×362) (theatlantic.com))

This point is illustrated in Figure 13, which for me shows a Dalmatian dog, but you can only see it is there if you have seen a Dalmatian dog before – otherwise all you see is spots. I can also make out maybe a tree and the edge of a path, but I don't think I can see anything I have not seen before. My view of the picture is conditioned, as with the ancient astronomers, by what is expected, what I have seen before. If I look closely, maybe I can see an aircraft, or the letter G, or face. What is really there? The Dalmatian is there because I have seen a Dalmatian before and there is sufficient evidence for my mind to build the dog from the dots. However, this could be a perfect picture of a widget – as I have never seen a widget – so I cannot see it now.

This is the case too with the VL. When I look at the VL then I see what I have seen before – I see a laboratory. The lines and shapes in the VL are, for me, beakers and pipettes, but I have seen such things before – my eye 'attuned' to such things (see, Duhem's description of a laboratory, in Hanson, 1962, pp. 16-17). Is it the same for a learner? Hanson (1962, pp. 15, 18) talks of an X-ray tube, how is it seen by a physicist (a scientific instrument), a schoolboy (a glass and metal object), a baby? In a VL do science students see same thing as history students, or as the VL designer, or as me? The VL will only be able to show learners what they are able to see. The interaction of the user with the VL will be unique to the concepts which they bring to the experience. This is probably the case with all learning interactions and is reminiscent of the 'zones of proximal development' proposed by Vitosky (Gregson and Hillier, 2015, p. 49). However, for the VL the interaction is much more tightly controlled, the learner is presented with a menu, carefully prepared by the chef; rather than the more do-it-yourself a la carte, in the real laboratory. Practical activities for students are often quite carefully scripted, especially at younger years, however, the outcomes are never guaranteed, there is always the possibility of an unexpected result (and particularly for physics experiments – equipment issues). It is often in these interactions of students with unexpected results that genuine inquiry can occur. This is not the case for the VL, the result will follow the theory, the observation will fall into an expected range and match the paradigm of the VL program constructor.

There now also raises the issue of the power dynamic presented by the VL. In the real laboratory, the instructor has the ability to direct and control, the situation. However imperfectly this is done, they still are able to exert influence. They in turn will be directed by the syllabus they are following and the norms and procedures of their institution and professional body. They will also (according to Kuhn) be part of a paradigm which will give them a particular world view. There will be many influences on the instructor. Furthermore, there will be the differing interaction of the instructor with each student, which will vary over time and mood. There will be a constant dynamic process in the interactions of learners with each other, the instructor, the environment and their own condition. Power and influence will be spread widely, many factors will interact, and the process of learning may be nuanced and unpredictable.

For the VL on the other hand, many of these factors are fixed. The interaction will occur in a predetermined way: this is both a benefit and a risk. The VL presents a fixed world view, the paradigms and theories are those of the creator – presented in a 'black box'. Hopefully, this box contains all that I want – an exact match to my paradigms and to the exam specification that the students are following, but I doubt it. Hanson (1962, p. 30) suggests that 'The paradigm observer is not the man who sees and reports what all normal observers see and report, but the man who sees in familiar objects what no one else has seen before.' Can we observe things in the VL which were not those intended by the constructor?

Causality

The concept of causality is vital to make sense of any VL. The relationship between an action and its consequence is an essential element of how a VL works. Any algorithm used will have an output which depends on the input in a predictable way. Within the VL if we do A the result will always be B. Is this always true in the real world, though? This is related to the problem of induction discussed in the next section. In this section I consider the concept of causality in more detail.

Russell (quoted in Hanson, 1962, p. 50) states, 'The chain of causation can be traced by the inquiring mind from any given point back to the creation of the world'; and presumably, by extension back to the creation of the Universe. This is the deterministic view, that any event is uniquely determined by previous events and that if we knew the state of the Universe precisely, at its creation, we would be able to predict any future event. This is the world of the VL. In a virtual world the rules of mathematics apply, and the outcome is certain. Even if 'pseudo-random' errors are introduced to simulate experimental uncertainty, the underlining structure of the algorithms will produce a predictable result. This process relies implicitly on the concept of induction, so for Hume, Goodman and others (see Chapter 3), this cannot be guaranteed in the real world. Hume sets out his analysis:

'

1. Neither reason nor experience gives ground for holding the future will resemble the past.
2. Cause and effect must be distinct instances, each conceivable without the other.
3. The causal relation is to be analysed in terms of contiguity, precedence, and constant conjunction.
4. It is not a necessary truth that every beginning of existence has a cause.'

(Kenny, 1997, p. 164)

Hume's rejection of causation leads to his similar problems with induction (discussed in Chapter 3).

Russell, on the other hand, can see an underling value in the concept of causation, he develops the idea 'that there are causal chains, each member of which is a complex structure ordered by the spatio-temporal relation of compresence…'; moreover, 'All the members of such a chain are similar in structure…' (Hanson, 1962, p. 50). The VL follows very much the pattern suggested by Russell. Hanson (1962) considers this idea of a chain of causality expanding it with examples from science. He notes that 'Laplace claimed that, were he supplied with an account of the state of the universe at one moment, plus a list of all the causal laws, he could predict and retrodict every other moment of the world's history' (ibid., p. 51). Again, this is just the approach underlying the VL. However, Hanson points out that physicists rarely discuss ''*cause',* much less *causal chain*… in the actual practice of physics' (ibid., p.52). Hanson then discusses examples of causal chains and points out that 'reference to one link of a chain *simpliciter* explains nothing about any other links. It does not even entail the existence of any other link'. The situation is more complex than a simple causal chain other factors need to be accounted for. Hanson suggests that the 'primary reason for referring to the cause of *x* is to explain *x*', but 'There are as many causes of x as there are explanations of x'. Therefore, we can have 'an explanation of *x* only when we can set in into an interlocking pattern of concepts about other things, *y* and *z*'. Developing these ideas Hanson claims ''causes' are theory loaded from beginning to end. They are not simple, tangible links in the chain of experience, but rather details in an intricate pattern of concepts'. Our VL needs to be a complex world of interacting effects, to satisfy Hanson's views. Hanson further develops the idea of language linked to causation and explanation, leading back to the 'theory-loaded' nature of observation. He gives the example of 'scar' and 'wound'- the scar is caused by a wound; but is it still a wound if it is a minor scratch? Or the careful incision of a surgeon during an operation? A similar critique of causality is developed by Cartwright (summarised in O'Hear, 1990, pp. 126-129), this concentrates on the relationship to theory and the difficulty in discerning any reasonable patterns in a complex environment. While Feyerabend (2010, p. 33) believes that 'no theory ever agrees with all the facts in its domain'. This is summarised by Bridgman (quoted in Hanson, 1962, p. 50) as '[w]e do not have a simple event A causally connected with a simple event B, but the whole background of the system in which the events occur is included in the concept, and is a vital part of it.'

So, when designing the VL, it may be that there are unexpected consequences – interactions which produce unimagined results. This is both in the VL where software may conflict or algorithms interact in unplanned and unthought of ways; and in the real world where, even accepting the validity of induction, there a multiple subtle interactions and unexpected consequences. This problem with causality is something to which we are probably naturally attuned: we do not expect everything to always go to plan. However, in the VL the effect of unexpected results can be more surprising and disconcerting – in some ways we expect the computer to produce a 'perfect world'.

Uncertainty

The fundamentally uncertain nature of quantum states, embodied in the Heisenberg uncertainty principle (Woods and Baumgartner, 2020; Hanson, 1962, p. 150), means that there cannot be absolute certainty of any real result. A VL is fundamentally different, in that, the result is mathematically predictable, as it is based on a computer program and therefore on a numerically expressed model. Some VL add a pseudo random noise to the measurement values to mimic experimental error, however, they still appear to be based on a fixed algorithm.

There is also an uncertainty in our how we perceive our experiences. Kuhn (1996, pp. 62-64) describes the experiment by Bruner and Postman, which shows how we see what we expect. While the expectation fits with experience we continue to hold it, only when the anomaly becomes great, do we accept there is an issue. In the context of VL, this suggest that once "in the zone" students will continue to believe in the experience until there is a serious cognitive conflict.

Summary of Chapter 2

To summarise the work on VL applications reviewed at the start of the chapter have shown that VL can provide a valuable learning experience in HE and to some extent in schools. This is particularly true when VL is used in conjunction with real laboratories. There is evidence that learning in a VL is different to that in the real laboratory and it promotes higher level learning of application of knowledge and the transfer to new situations. However, most studies are small scale and may not have sufficiently robust methodologies for confident transfer of conclusions. There is a dearth of information about FE applications of VL; however, it is likely that the results from HE and schools are applicable; so, FE students will also benefit from their experiences of VL.

The experience of students using VL appear to be largely positive, however, not as positive as experiences reported for the real laboratory. The main issues seem to be related to emotional matters – a dislike of the feelings generated by this way of learning. Learning in the VL is possibly best described from a constructivist perspective (see Zendler and Greiner, 2020; Govender, 2023).

There is a considerable body of literature concerning the importance of practical studies in science, for example Dillon (2008) and Holman (2017). Practical science has been discussed as an important educational tool, and a number of specific outcomes can be identified; those given by Holman (2017) are used in this study. These outcomes are not matched exactly by those provided by VL. However, VL can provided a different and possibly more easily scaffolded learning structure.

The VL can be viewed in terms of different educational perspectives. The behaviourists (Skinner, 1954; see Gregson and Hillier, 2015, pp. 39-41) view is that experiments are performed in a structured way to demonstrate predetermined outcomes. Students learn by observing the outcomes of the experiments, repetition helps with the reinforcement of learning. For the behaviourist the VL is ideal, with predictable methodologies, results and rewards, as well as, the opportunity for multiple repetition. As Gregson and Hillier (2015, p. 40) comment 'Some computer programs are particularly successful in reinforcing and shaping learning'. The 'black box of the students' minds' mirroring the black box of the VL; the focus is on input leading to output. The cognitive perspective (Ausubel, Hanesian and Novak, 1978; see Gregson and Hillier, 2015) has more questions to ask of the VL. The learner's mind is central here and how understanding is developed over time, this perspective is perhaps more in line with the real laboratory experience. Kolb's concept of experiential learning (Gregson and Hillier, 2015) where the VL provides a concrete experience. Similarly, the idea of situated learning within the virtual laboratories can be enhanced by the use of 'game' type scenarios. While, cognitive (Piaget, 1977) or radical constructivism (Glasersfeld, 1995) are probably the most appropriate perspectives for describing VL; since VL provides little social interaction required by a for social constructivism perspective (see Gregson and Hillier, 2015, pp. 48-50).

There are fundamental questions about nature of reality which are relevant to the use of VL. Starting from the perspective of O'Hear (1990, p. 130) who maintains that 'the contemporary philosopher of science…is likely to accept the world and its inhabitants as a starting point' and 'that there is a world independent of those who observe it'. The understanding of the way 'scientific truths' emerge has an intimate bearing on how the VL is considered. Is it intended as a mirror of reality, for Sennett (2009, p. 85) a 'replicant' or an enhanced learning tool (Sennett's robot; ibid) based on a 'theory laden' perspective?

The VL depends on the Universe being deterministic, without which we run into problems with causality and induction (discussed in Chapter 3). The concept of a VL is predicated on the ability to predict the future from a known starting point – the concept of Laplace's 'deductive chain' (Hanson, 1962, p. 51). The concept of time is also crucial to the experience of the VL. In many VL configurations it is possible to manipulate time, speeding up, slowing down stopping and reversing processes.

For some science is about obtaining facts, these are then interpreted and explained by theories based on the evidence available. This is not, however, how many authors have viewed the historical development of science. Kuhn (1996) has argued that science proceeds in two distinct phases 'normal science' and 'revolution'. Once a theoretical interpretation becomes established a period of normal science occurs, during which, scientists accept the 'paradigm' and work within it to solve problems. Eventually, problems occur which cannot be solved within the existing theories and a revolutionary change occurs. Kuhn (1996) and Hanson (1962), then view the observations of scientists to be 'theory-laden'; 'facts' depend on the perspective of the observer. Considering VLs, these are tied to a paradigm and so will only be appropriate during the periods of normal science. Polanyi (Redman, 1993) sees scientific knowledge as in part in the 'tacit' knowledge of individual scientists, this might also be thought of as knowledge held within a VL. Sennett (2009) has suggested that the transfer of this type of knowledge can be viewed through a 'master – apprentice' model, with perhaps the VL acting as the 'master'. While the real, practical science laboratory might be described as one of Shulman's (2005) 'signature pedagogies', it is not clear that the VL can be regarded in the same way (yet).

CHAPTER 3

METHODOLOGY

'What is truth?'

(St. John, 18:38)

Introduction

In order to decide on a methodology, I need to decide what I want to know.

In order to decide what I want to know; I need to decide what knowing means.

In order to decide what knowing means, I need to decide, what knowledge is.

In order to decide what knowledge is, I need to decide what facts are.

In order to decide what facts are, I need to decide what is real.

In this process I have taken the view that I am making the decisions – my view of reality is subjective. But can I view the world objectively? Is there any standpoint which I can use which will give me a view similar to other peoples?

The first point which need to establish – is there an objective reality – a state of being which exists independent of the observer? I believe there is. I believe that there is a state of being outside my mind which has some existence independent of me. I may never know much about it, but I accept it exists.

So, what is real? There are two main traditions which claim to be able to throw light on this problem:- realist and constructivist. Realists hold that reality is 'reductionist and deterministic' (Waring, 2017, p. 18); it is subject to time and context free laws of cause and effect. Alternatively, constructivists suggest that an individual reality is constructed by the mind. The constructivists rely on the interpretation of reality, informed by the theories and experiences of the observer. This view of reality is personal to the observer.

The ideas of what exist, and is real, is studied in the philosophical discipline of ontology and has been the subject of debate for centuries (Russell, 2000). Usher (1996, p. 11) suggests ontology is 'about what exists, what is the nature of the world, what is reality'. These ideas have a dual importance in this work as I am concerned not only with the questions of reality which I hope to illuminate though appropriate research, but also the concept of reality experienced in virtual and indeed real laboratories.

A second strand of philosophy – 'epistemology' is 'concerned with what the criteria are that allow distinctions between 'knowledge' and 'non-knowledge' to be made' (Usher, 1996, p. 11). The question arises as to the difference between knowledge and opinion (or belief). This argument has also run for many centuries (see Russell, 2000; Okasha, 2016).

The realists or positivists 'discover' facts which are the basis of knowledge. They use the methods of experimental science with the independent investigator making 'presuppositionless' observations (O'Hear, 1990, p.16), in a controlled environment. Knowledge is developed though hypothesis and theory, grounded in the results of empirical experimentation and observation. Alternatively, interpretative approaches do not ‘see direct knowledge as possible; it is the accounts and observations of the world that provide indirect indications of phenomena’ (Waring, 2012, p. 16). This suggests that all knowledge is mediated through the observer. Waring goes on to say ‘that knowledge is developed through a process of interpretation’ (ibid). Hanson (1962, p. 19) perhaps goes further than this suggesting ‘observations [rest] in the language or notation used to express what we know, and without which there would be little we could recognise as knowledge’. Observation and therefore knowledge construction is ‘shaped by prior knowledge’ (Hanson, 1962, p. 19) and inherently ‘theory-laden’.

Derived from these perspectives are methodologies which describe how we should proceed in the process of research. Waring (2012, p. 16) says that ‘methodology asks ‘what procedures or logic should be followed?’’. This gives a steer to what might be expected as a focus for investigation during research. Positivists would favour the deductive logic, working from general laws to investigate particular cases. This is the driver for Popper’s theory of ‘falsification’ (see Chapter 2). However, there is little ‘real world’ evidence that deductive logic can be applied to non-trivial problems. As O’Hear (1990, p.27) puts it ‘the conclusion cannot go significantly beyond the premisses’ – a deductive process can tell you little more than you already know. The alternative interpretative approach relies on inductive logic, which as we see below, Hume, Goodman and Popper severely question.

In Part 1 of this chapter, I further explore ontology and epistemology, which were discussed in Chapter 2. The focus now, however, is the bearing these have on the structure and nature of data this study. Starting with the three areas of Greek philosophy: ontology, epistemology and value judgment; I apply these to my research in VL.

In Part 2 of the chapter, I use the ideas from Part 1, to help define a methodology for the study. There is also some detail on the way the study was carried out and the methods used to obtain data.

Table 14 showing the basic assumptions fundamental to the positivist and interpretive paradigms from Coe et al (2012)

Assumptions	**Positivism**		**Interpretivism**	
Ontology	**External Realist**	Objective reality exists in a deterministic Universe	**Internal – idealist, relativist (Local and specific constructed realities, holistic and dynamic)**	All experience is subjective. It is subject to the prior experience and theory-laden
Epistemology	**Dualist Objectivist**	Knowledge is gained through 'presuppositionless' observation by rational observers. Theories are built on and tested by experimental data.	**Subjectivist, transactional, interactive**	Knowledge is gained through the interpretation of sensory observations, in the contexts of both theory and past experience.
Methodology	**Nomothetic, Experimental, Manipulative: Verification of Hypotheses**	Methods are based on the assumptions of causality and that data can be analysed objectively. Experiments are designed to test hypotheses and 'verify' or 'falsify' theories.	**Ideological, dialectical hermeneutical**	Methods are based on interactions. Actors interpret the world through their interactions with others and their observations are 'negotiated' within the context in which they are made.
Enquiry Aim	**Explanation, Prediction and Control**	Progress through better explanations of observed phenomena generating more accurate theoretical models.	**Understanding interpretation and reconstruction**	Context based understanding of a situated problem, through the interaction of the participant-observers.

PART 1: PHILOSOPHICAL PRINCIPLES

‘philosophical insight is—in my opinion—the mark of distinction between a mere artisan or specialist and a real seeker after truth’

(Einstein, in Howard and Giovanelli, 2019)

Ontology

Ontology is, as discussed above, about reality, ‘a particular theory about the nature of being or the kinds of things that have existence’ (Merriam-Webster Dictionary, 2015). There are a range of views about what is real and as with other areas of philosophy considerable disagreement. Table 14 sets out the basic assumptions for the two main interpretations – positivism and interpretivism; a third interpretation – pragmatism, is also relevant to this study. The difference between the positivist and interpretivist approaches can be seen as a ‘continuum’ (Waring, 2012) or incommensurate paradigms – ‘you believe the world exists independently of our knowledge of it, or you don’t; there is no middle way’ (Coe, 2012, p. 8). While pragmatism might be viewed as ‘an anti-philosophy not another paradigm’ (ibid). To gain a balanced view of any research in the field of education it is necessary to understand the perspective of the researcher – this is arguably even more in the case of practitioner-research, such as this, where the researcher is also part of the story.

In Chapter 2, I discussed the ‘scientific’ view of reality and how that frames views of the VL as an alternative view of reality. Here I want to concentrate on the process of research and how the results of this study reflect reality. I accept, along with others, (O’Hear, 1990) that there is an objective reality. However, I do not believe that I or anyone else can fully experience or describe it. All experience is modified by our viewpoint. The ideas of Hanson, Kuhn, Feyerabend, Dewey and others discussed in this work, suggest to me that we can never see with ‘presuppositionless’ eyes. My language, culture and education shape how I see the world and however ‘objective’ I try to be, I cannot see exactly the same as others. In the next two sections I expand an illustration and description my ‘personal’ view of the world.

The spinning-top

Figure 14 shows a simple illustration – my son’s spinning top. When stationary I can clearly see blocks of colour in rings around it, these to me look pink and blue; blue and yellow; yellow and pink; blue and white. Figure 15 shows the same top, spinning; now, the colours I see are purple, green, orange and light blue. Physically, nothing has changed about me or the top, we just have a different relationship to each other. The colours remain the same, it is my *experience* of the colours which change: this is the point which Dewey makes ‘The world as we experience it is the real world’ (Biesta and Burbules, 2003, p. 25). So, my reality changes as the top speeds up – there is a ‘Gestalt switch’, and yet, if I were able to sit on the top as it is spinning, I would still see – pink and blue; blue and yellow; yellow and pink; blue and white. This is the same point that Goodman makes about ‘grue’ (see below), which for him invalidates induction. For me I have the problem that when I describe my research (or indeed when teaching) I need to specify where I am standing. If I were to describe the colour blue as that seen on certain sections of the top I am, myself clear what I mean, the colour in blocks A, B and C are what I would describe as blue. However, if see the top spinning, looking at Figure 1Figure 15 rather than Figure 14, you will see three different versions of ‘blue’.

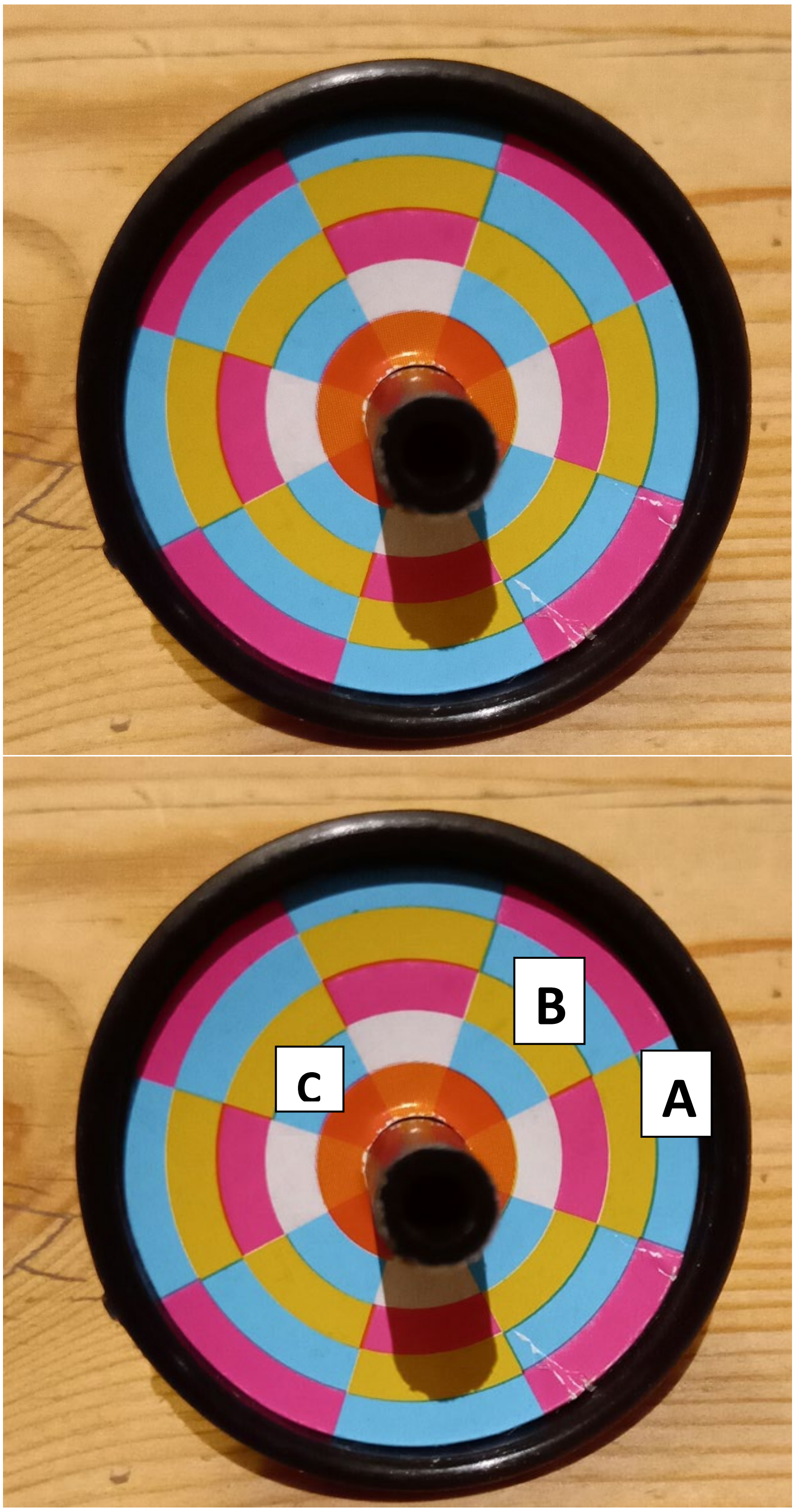

Figure 14 showing the stationary spinning top, in the lower picture the areas of ‘blue’ are labelled.

Figure 15 The spinning top – I can see the colours – purple, green, orange and light blue.

The top highlights, a number of considerations:

1. Even though I can clearly specify A, B and C, as the same colour, that is for me blue, I cannot be sure that an observer has the same viewpoint and so does not see, what for me, is purple, green and light blue.
2. The top is a physical 3-dimensional object which viewed from the side looks like a short arrow and from the bottom as a black disc. The concepts of colour and spinning have little relevance to the top viewed in these ways.
3. There are many factors which might change a perception, I cannot be sure what is important in the context of describing my results (or in conveying any other information). I cannot describe all the factors, even if I am aware of them. Scruton (O'Hear, 1990, p. 45) describes the use of the term 'ornamental marble' by masons to describe a type of stone. There are three types, porphyry, onyx and marble, which have the same properties for the mason carving the stone. However, these are chemically very different materials; thus, for the chemist or geologist, these are completely different materials.
4. A further analogy is given by the property of angular momentum, that a spinning object possesses. This gives a resistance to changing the rate of spinning. Energy, or effort, is required to change the rate of turning. So, to look at the stationary top, gives one view, or at the spinning top another, but to change viewpoint from one to the other needs effort to slow down the top or speed up the observer. It is also true when trying to explain results or concepts, effort is required to change from one viewpoint to another.

So, when I am describing the 'reality' of my results I need to bear in mind that my viewpoint is not that of others – what is obvious to me, may be incomprehensible to them. This is expressed by Kuhn in terms of paradigm shifts and also by Hanson as Gestalt switches (see below). There is an incommensurability between the perception of the stationary top and the same top spinning. You have to change your point of reference to see the same things in both paradigms. Dewey (1933, p. 53) describes how children are slow to recognise colours which are for an adult 'so glaring that it impossible not to note them'. The colour 'of the object does not tend to call out a reaction that is sufficiently peculiar to give prominence' (ibid). Yet as we saw in the example above what is 'glaringly' obvious from one perspective, is a confusing contradiction from another. This suggests that my results should be presented in such a way as to give the reader a ‘sense of the whole … built from a rich data source’ (Connolly and Clandinin, 1990).

Thought

When I think, when I am conscious of thinking, I am aware of an internal monologue. To me it feels like this is going on in my head, it is located in that space. It is also located in time, I am aware that it happens, like now, and there are other times when I am not really thinking in this way there is no explicit monologue. I am conscious that my thoughts are in English, they are formed in words in my head, I create sentences, explanations, linguistic devices, and all are basically in English – my mother tongue. I cannot effectively speak another language, I leant some French at school and some German and even less Spanish, at evening classes. I have never formally studied music and cannot read or write music, but I can make up a tune in my head. I have learnt something of the language of maths and science. I can think in formulae and carryout simple mental arithmetic. I can hold the picture of molecules in space and imagine movement in 3-dimensions. Realistically, I have no idea how anyone else thinks. The only pattern I have is the way I see the world. I have to assume that you see essentially the same thing in the same way; but how can you? No one else has the same DNA, the same physiology, the same brain structure, the same experiences, everyone is truly unique.

How then do I know about the world? If I think in language, then my view of the world must have changed. When I was born, I had no formal language, this I learnt, largely from my parents, but also from others around me. I learnt the concept of ‘dog’ not just my dog, ‘Minnie’, but other similar, animals, which were not exactly the same, but had many of the same features; and that ‘Cats’ are different – the problem of universals (see Russell, 2000; Kenny, 1997). Looking now at these ideas I formulate them in terms of patterns. Although when I think of things on a day-to-day basis I do not consciously think in patterns, when I think about how I think, then I see patterns. I am conscious of how I make meaning out of an experience by comparing it to previous experiences, matching it to the pattern of events, or objects. The significance of patterns is considered in more detail in a later section.

Pragmatism

Dewey’s philosophy provides an alternative interpretation, where it is experience which is the key feature. Thus each experience is a unique ‘transaction’ which occurs each time ‘as processes of the full situation of the organism-environment’ (Biesta and Burbules, 2003, p. 27). Coe (2012, p. 8) describes ‘pragmatism, [as] rejecting the traditional philosophical dichotomies of realist vs. idealist ontology’. Claiming that ‘it is not just another philosophy but is itself an anti-philosophy not another paradigm’. So, a completely different view of the world incommensurate with the dualist ontology.

I have a good deal of sympathy for the pragmatic approach, which is in tune with the Heisenberg’s uncertainty principle (Biesta and Burbules, 2003, p. 27) and that ‘the very process of observing and measuring has direct consequences on the characteristics of the particles being observed’. However, this leads to the problem that as an observer – does anything happen when I am not watching; an issue posed in the problem of Schrödinger’s cat. A second issue is thought; I have the impression that that although my thoughts are influenced by the environment, they do not necessarily ‘transact’ with it, they seem to have a separate existence; but maybe this just because I do not really understand Dewey’s ideas.

Thus, pragmatism, in the sense used by Dewey, is a rejection of the positivists' objectivity and the interactionalists' subjectivity, giving a different perspective based on 'transactional realism' (Biesta and Burbules, 2003 p. 11). Dewey identified that there is a crisis in the dualistic approach based on the ideas of Descartes. This separates the mind from the world around it and leaves the problem of how the '(immaterial) mind can get in touch with the (material) world' (ibid, p. 10). Dewey's solution is to recast the problem and consider instead 'the *interaction* between elements of human nature and the environment, natural and social' (ibid, p. 10). This third way, based on generating knowledge through process of 'transactional constructivism', 'goes beyond the traditional distinction between objectivism and relativism' (ibid, p. 11). Knowledge then is a construction, but 'not a construction of the human mind, but a construction that is located in the organism-environment transaction itself' (ibid. p. 11). This ensures the inclusion of value judgments and ethical considerations as part of the process of knowledge generation, since these are already located in the interaction. This addresses the problem created by a mechanistic world view of either 'the *inhuman rationality* of science or the *human irrationality* of common sense' (ibid, p. 17).

The key feature for Dewey, as it was for Hume, (Warburton, 2001, p. 102) is *experience:* 'the world *as we experience it* is the real world' for Dewey (quoted in Biesta and Burbules, 2003, p. 29). A further quote from Dewey in which he describes the interaction of an organism with its surroundings, sums up the idea of experience and is directly related to the process of inquiry (discussed below). 'The organism acts in accordance with its own structure, simple or complex, upon its surroundings. As a consequence, the changes produced in the environment react upon the organism and its activities. The living creature undergoes, suffers, the consequences of its own behaviour. This close connection between doing and suffering or undergoing forms what we call experience' (from Dewey, 1920, quoted ibid, p. 28). This is an important statement when considering VLs for several reasons. Firstly, it reminds us that there is an interaction between student and VL, neither the student nor the VL are passive, each alters the other during the interaction. The VL responds to the actions of the student's input, in a way which depends on its level of sophistication. The user is then altered by the action of the VL and responds to its changing output. This process might be regarded on behaviourist level as a simple response to a stimulus. Secondly, there is hopefully, a deeper process of learning, recognising or understanding for the student, but also for the more sophisticated VL, which is programmed to respond when a user makes an 'error'. Thirdly, there is an element of inquiry for the student, both in the behaviours anticipated by the programmer and beyond this, in how the student tests the 'edges' of the VL. Arguably, this has become a *transaction* between the learner and the programmer, mediated though the VL. Another factor is the *experience* of the student in the VL interaction. From the statement above Dewey requires an active element in the process of experience. For there to be an *experience* in this sense it would seem the student must be engaged – there must be some form of action to which the student responds, and part of that response changes the student – they learn – and this informs their response in the future.

The nature of truth

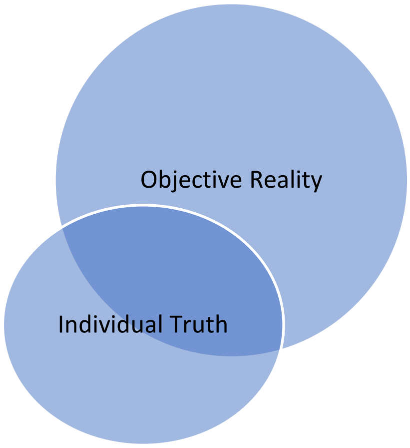

Figure 16 showing a schematic of my ontological view.

My ontological view is summed up in Figure 16, which is similar to that proposed by Kant, (Warburton, 2001, p. 131). Sitting somewhere between positive and interpretive perspectives, in accepting an objective reality, but not that it can be known objectively. This is also similar to Dewey's pragmatic approach, but I believe that there can be knowledge without a 'transaction'. I can experience the light from stars without a 'transaction' – I did not exist when the light left a distant star and it may well not exist when it reaches me; and when any possible effect I could have reaches the star, I will no longer exist – my experience can then never be a 'transaction'.

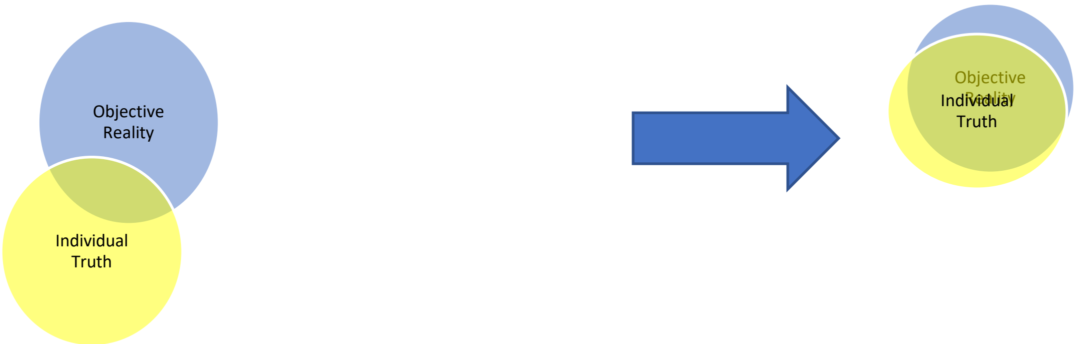

Figure 17 showing the effect of education moving the individual truth closer to the objective reality.

For this model of individual truth and objective reality, one would hope that with education, as shown in Figure 17, we move the two closer together. If we accept a fixed objective reality then education must modify individual truth, that is change the way we perceive the world. This is predicated on the idea that the teachers view of reality is closer to the truth than the student. This assumption is then a major theme in the study discussed in this thesis.

Epistemology

'When I think about the ablest students whom I have encountered in my teaching, that is, those who distinguish themselves by their independence of judgment and not merely their quick-wittedness, I can affirm that they had a vigorous interest in epistemology.' (Einstein, in Howard and Giovanelli, 2019)

Epistemology is 'the study or a theory of the nature and grounds of knowledge especially with reference to its limits and validity' (Merriam-Webster Dictionary, 2015). There is of course a long and often heated philosophical discussion about what knowledge is and how it can be obtained. In this section I will review some of the concepts and ideas relating to how knowledge is generated and transmitted. I will try to set out the position I have adopted in this work, in Part 2 of this chapter..

I start by relating the importance of theory to the epistemology relevant to this study and the relationship to how we 'know'. Much of epistemology appears to be related to how things are known and with the logical arguments based on the processes of deduction and induction: these are discussed next. Following, this there is a discussion of how these ideas have been expanded to provide methods of generating knowledge from observations and the different perspectives that have been applied. The section is concluded by a discussion of how knowledge is held in patterns.

Theory

Theory is essential to the VL, without the concept of theory the VL is impossible. A theory allows us to abstract an element from the mess of observations and relate it to another element. It is that relationship which the theory provides that allows the concept of a VL to exist. We have seen from the previous discussions that the reality of space and time are uncertain and to some extent, at least, subjective. A theory can provide a rock of objectivity in the changing patterns of the sea. It is often easier for us to accept a theory than the evidence of our own eyes for example, we expect to see the sun rise in the East, even though we saw it disappear in the West some hours before. In fact, we expect to know to within a minute when the sunrise will occur each day – even though it changes from day-to-day. Observation tells us the Sun has gone – theory that it will return. In the VL we use theory to generate 'observations'; so, it is the underlying theories which determine what we experience. This lays particular emphasis on which theory, or theories are used. There is in a sense a political choice about this; and this is further discussed below. Here I want to concentrate on the scientific choice of a theory. There is then a question about what is the 'best theory'. Kuhn (1996, pp. 94, 109-110, 147-159), maintains that there is no best theory, it is not possible to rank them as each is associated with a different and incommensurate paradigm; although he does give five criteria which he regards as important (Kuhn, 1977, pp. 321- 322). Cartwright (in O'Hear, 1990) suggests that we should look at theories to supply only local solutions, and not expect a theory to be applicable universally, (c.f. Feyerabend, 2010) for example the incompatibility of quantum and relativistic physics. This is also discussed by Hanson (1962), who cannot see a 'logical staircase running from the physics of 10^{-28} cm to the physics of 10^{28} light-years. There is at least one sharp break' (Hanson, 1962, p. 157). He gives an extensive argument, based largely on the uncertainty principle, to show that there is 'conclusive evidence that the languages are different, logically discontinuous'; this is developed by Kuhn (1996) in his theory of incommensurate paradigms. However, some take a holistic view of science and are working towards a unified theory of everything (see for example, Webb, 2021).

In the VL the choice of theories is an essential feature of how they will perform. This will be related to a number of factors which may have scientific, educational, aesthetic and commercial dimensions.

The final choices maybe obvious to users, however, in more sophisticated representations it may not be clear even to the coders which theoretical model is dominant in causing a particular simulated phenomenon. This lack of transparency of the 'black box' is discussed, below.

Despite Kuhn's misgivings and assertion that there is 'no algorithm' (Okasha, 2016, p. 84) it will still be necessary to make a choice about which theory is the 'best' or most appropriate for use in a particular VL. Even the best way to generate a theory is not clear as Russell (2000, p. 529) says 'framing of hypotheses is the most difficult part of scientific work' and that 'no method has been found which would make it possible to invent hypotheses by rule'. There have been several suggestions as to how theories can be 'discovered' and compared; these are discussed below.

Deduction

The logical method of deduction is closely aligned to mathematics; Russell (2000, p. 49) describes mathematics in terms of a 'demonstrative deductive argument'. The VL is built from mathematical rules which are known *a priori*. As Russell (2000, p. 55) iterates, the process for geometry, 'starts with axioms which are (or deemed to be) self-evident and then using deduction'. The logic that the VL uses is mathematical and therefore partly deductive. Once the axioms or premises of the VL are established these entail the subsequent results. As stated by O'Hear (1990) and Okasha (2016, p. 17), for deductive inference, 'if the premises are true, then the conclusion must be true too …the premises of this inference entail the conclusion.' Further, 'What makes the inference deductive is the existence of an appropriate relation between premises and conclusion' not truth or otherwise of the premises, but if the premises are true this 'guarantees the truth of the conclusion'. The VL then relies on the 'truth' of the premises, if we can be sure of these and we use deductive logic our results will be true.

Much of the basis of the deductive method is due to Aristotle. Russell (2000, p. 206) describes 'Aristotle's most important work of logic' as the idea of the syllogism. A syllogism is a logical argument based on three parts: 'a major premise, a minor premise and a conclusion'. Russell (ibid, p. 206), Sennett (2009, p. 212) and O'Hear (1990, p. 26) give the classic example:

'All men are mortal (Major premise).

Socrates is a man (Minor premise).

Therefore: Socrates is mortal (Conclusion).' (Russell, 2000, p. 206)

Russell goes on to describe the four different types of syllogism based on this type of construction. These provide a form of logic which can be used to infer guaranteed conclusions according to the premises. Russell (2000, p. 207) offers three main criticisms of the syllogistic method:

1. Formal defects, such as a fault in the coherent application of logic to all steps in the syllogism, errors can occur due to unclear definitions; in particular, the distinction between particulars and universals.
2. Over-estimation of the syllogism. Russell points out this is not the only deductive method and as Kant recognises 'mathematics is not syllogistic' (ibid, p. 209).
3. Over-estimation of deduction. The main problem here is the validity of the premises. Using Russell's example (ibid, p. 209), how do 'we know that all men are mortal'? In fact, what we know, Russell claims, is that 'all men born more than one hundred and fifty years ago are mortal' and this is our reason for believing that all men will die. This is an inductive, not a deductive argument, we cannot be certain of the original premise, however, it is very probably true.

Russell (ibid, pp. 209-210) goes on to say that ‘All important inferences outside logic and pure mathematics are inductive’. Furthermore, Sennett (2009, p.212) argues ‘Inductive leaps defy syllogisms’ and points out Bacon ‘argued that syllogisms can be misleading’. Further ‘Syllogistic thinking, Bacon declared, is not much good for ‘inquiring into truth’ of the first principles’ (ibid, p. 213). Hanson (1962, p. 108) discusses establishment of premises by reference to Newton’s laws and how these should be considered – as hypotheses, empirical facts, or a priori truths; and therefore, if they are suitable as the basis for deductive logic.

In summary, Russell (1948, pp. 171-172) says ‘deduction has turned out to be much less powerful than was formally supposed; it does not give new knowledge, … stating truths in some sense already known’. However, Einstein (in Howard and Giovanelli, 2019) ‘The supreme task of the physicist is … the search for those most general, elementary laws from which the world picture is to be obtained through pure deduction’. This is in line with the deterministic view of the Universe discussed above.

This gives us an interesting viewpoint for the VL, which is based on mathematics and therefore, in part, deductive logic. We can guarantee that the outcome of VL is logically consistent with the premises which set it up (barring errors of logic), but we cannot guarantee that the result will be valid scientifically, this will depend on the premises used. We are left with determining the original premises by some non-deductive means. For the VL as well as life the maxim ‘garbage in – garbage out’ (DCS, 2016) holds and we need great care in specifying the premises or underlying theories used.

Induction

The method of induction is a widely used way to develop theories. Simply observations are made and then patterns are looked for in the data. The method was developed by Bacon (O’Hear, 1990, pp.12-21; Kuhn, 1996, p.16; Sennett, 2009, pp. 212-213; Hanson, 1962, p. 70; Russell, 2000, pp. 526-530) requires presuppositionless observation as the basis of ‘facts’, which are then tabulated systematically. For Bacon the observations should enumerate examples: these are then built inductively into a theory (see Mill, 2010). Bacon is clear that the process of enumeration should not be ‘the simple piling up of evidence in favour of theories’ (O’Hear, 1990, p.16) but a genuine test of competing theories (see Popper, 2002). This method for discovering theories is criticised by O’Hear (1990, p. 20) as it is not possible to ‘observe *everything*, even in a delimited segment of time and space’. This leads to a need for selection – we need to know what to look at – this requires some prior selection of the significant data – otherwise ‘the mere multiplicity of facts is baffling’ (Russell, 2000, p. 529). This point is illustrated by considering the tides, even the most careful recorder of observations, would be unlikely to record the position of the moon, without have some prior concept of gravity. Especially, as for many of the observations of the height, velocity, density, colour, temperature, acidity etc. of the water, the moon would not be even visible. Moreover, O’Hear (1990, p. 18) points out that in order to build up ‘lists of instances’, data needs to be categorised. It is necessary to classify events ‘under certain concepts, in order that the events can be seen as like or unlike each other’.

As Joos points out (in Hanson, 1962, p. 70) ‘As soon as we inquire into the reasons for the phenomena, we enter the domain of theory, which … connects the observed phenomena and traces back to single ‘pure’ phenomena, thus bringing about a logical arrangement’: this is the heart of the inductive argument, championed by Bacon and Mill (O’Hear, 1990, p. 25; Russell, 2000, pp. 526-530; Mill, 2010). The inductive method, following the four stages proposed by Mill (2010) (also see, O’Hear, p. 25-26) requires the presuppositionless collection of data to be tabulated; then ‘to isolate the features which are constantly associated with the phenomenon we are interested in’; to draw inference, from positive (or negative, or lack of) correlation within the data, that the feature is a cause of the phenomenon – creating a generalisation; and then to test this generalisation under new conditions.

This inductive method forms the basis for how students are taught about the scientific method - 'How Science Works': for example, the National Curriculum (2014, p. 3) requires students to be taught 'that science progresses through a cycle of hypothesis, practical experimentation, observation, theory development and review'. This follows the steps proposed by Mill (2010) but notice that the presuppositionless, required by Bacon, is now replaced by an explicit direction of observations towards a hypothesis.

It is not clear that a reliance on inductive methods is appropriate either in the development of science or in the consideration of VL. There are a number of criticisms of induction as a method in science, for example, Einstein (quoted in Hanson, 1962, p. 119) argues 'There is no inductive method which could lead to the fundamental concept of physics … in error are those theorists who believe that theory comes inductively from experience'. Similarly, Popper (quoted in Redman 1993, p. 31) maintains that for science '*there is no induction*: we never argue from facts to theories, unless byway of refutation or 'falsification.'' This causes a problem when we consider the VL, with theory and observation tightly linked and no possibility of falsification. So, Popper might well argue that the VL is 'unscientific'.

Furthermore, Russell (2000, p. 419) points out that 'induction is not valid as a logical principle'. While a more fundamental problem for induction is presented by Hume (Bird, 1998, pp. 15-17; Okasha, 2016, pp. 20-23; O'Hear, pp. 27-28) that 'the use of induction cannot be justified at all' (Okasha, 2016, p. 20). Hume argues that induction presupposes the 'uniformity of nature' (quoted in Okasha, 2016, p. 20) and there is no justification for believing this to be the case. As Bird (1998, p.16) points out 'experience can only justify the uniformity premise if we can expect cases we have not experienced to resemble the ones we have experienced'. Moreover, to argue that induction is justified as it has worked in the past is purely an inductive argument – 'it is to use induction to justify induction' (ibid p. 16) – a circular argument. Furthermore, Hume, is critical of the concept of causality (Kenny, 1997, pp. 164, 165) which is a prerequisite for induction to give useful results.

Goodman develops a further argument against a reliance on induction. He points out that our view of the future depends on how we categorise things, 'that two sets of people could approach the same evidence with different categories and come to different conclusions about future examples of the same type of thing' (O'Hear, 1990, p. 29). As an example, Goodman (Bird, 1998, pp. 17-20; O'Hear, 1990, pp. 29-33), considers the colour of emeralds, all of which, so far, have been found to be green. He suggests that they may in fact be 'grue' – a colour which appears green before a certain date (writing in 1954, he used 2000) and blue after that date. So, all emeralds examined before the date are both green and grue; however, after that date they would still be grue but appear blue – thus all emeralds cannot be both green and grue. Goodman summed the point up 'To say that valid predictions are those based on past regularities, without being able to say which regularities, is quite pointless. Regularities are where you find them, and you can find them anywhere' (O'Hear, 1990, p. 31). The whole concept of VL is based on 'regularities', that we can predict the behaviour of 'virtual materials' based on a set of characteristics which have been predetermined. Moreover, that the characteristics are the ones relevant to the behaviour, under the conditions, which are expected to exist in the VL. This leads on to the consideration of 'natural kinds' (groups 'of phenomena occurring naturally in the physical world with the same underlying physical constitution' (O'Hear, 1990, p. 17)), which is of considerable philosophical interest (see O'Hear, 1990, pp. 17,18,45,46; Bird, 1998, pp. 95-120). This is very relevant to the VL, where the properties of the 'virtual materials' in the laboratory are due to their categorisation. As an example, if we consider two solids (hydrated barium hydroxide and solid ammonium chloride) which react to form a liquid and gas, while the temperature falls to around -20^{o} C (RSC, 2022). This is a reaction which reverses many of the categorisation assumptions which might be built into a VL. The choice of category for a material will determine which theories and therefore algorithms should be used.

So, whereas the VL operates on a micro level according to mathematical (deductive) principles, at a higher level, in terms of how 'virtual materials' behave there is a reliance on induction. The algorithms which are chosen to be applied are those which are 'expected' to be appropriate for the materials and conditions of the experiment. Assumptions have to be made regarding categorisation and choice of theoretical model and these will be based on 'experience' and so using inductive inferences.

Popper (in Redman, 1993, p. 29) takes a more extreme view, suggesting that 'induction is invalid in *every sense*, and therefore *unjustifiable'*. He goes further than Hume in declaring that 'I hold that neither animals nor men use any procedure like induction, or any argument based on the repetition of instances. The belief that we use induction is simply a mistake. It is a kind of optical illusion' (in, ibid, p. 29). If Popper is right, then the basis for using a VL is illusory.

Explanation - Covering law

An alternative method for establishing knowledge is proposed by Hemple who suggests a deductive-nonological system (Bird, 1998, pp. 67-72; Okasha, 2016, p.37-44) of explanation reminiscent of the syllogism, discussed above. In this case, observations (O_1, O_2, …) are explained by reference to general laws (L_1, L_2, …) and specific conditions (C_1, C_2, …). This can be set out as:

Laws	L_1, L_2, …
Conditions	C_1, C_2, …
entail	________________________
Explanandum	O_1, O_2, …

(Bird, 1998, p. 68)

The explanandum – that which needs to be explained, the observations – are seen as a direct result of the overarching laws and the special conditions pertaining to the system. The laws and conditions are explans or things which explain the outcome. This method is sometimes referred to as the 'covering law' (there is also a probabilistic version, see Bird, 1998, p. 69; also, see Putnam's Schema, discussed in Chapter 5).

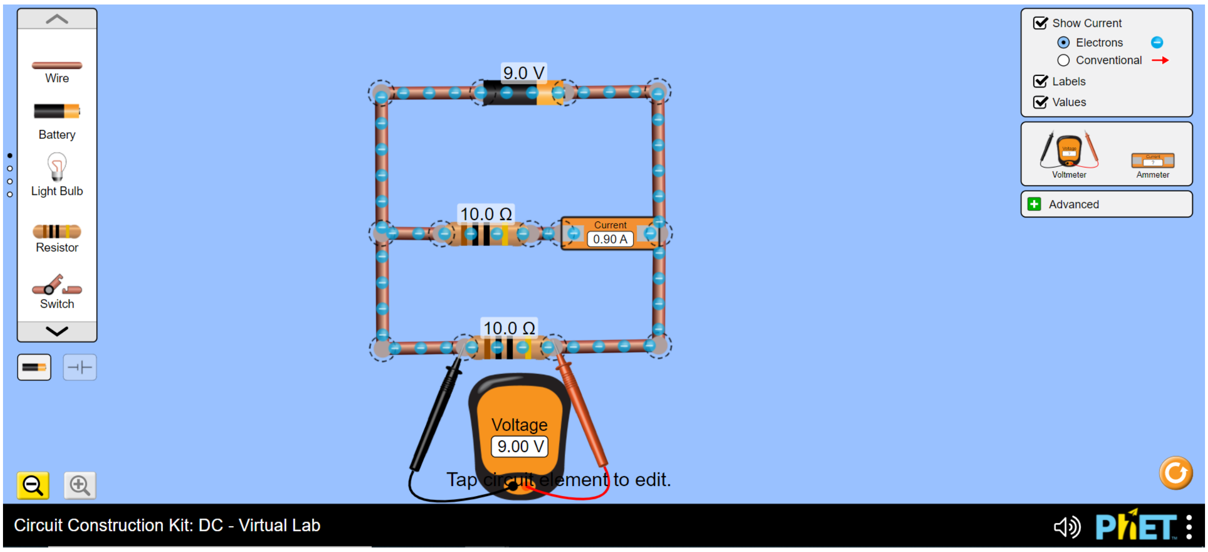

Figure 18 showing the construction of a parallel circuit using the PhET Virtual Lab, component values are shown in the figure.

Produced using the Phet simulation: http://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_en.html

This method is illustrated by using the VL of an electrical circuit (shown in Figure 18) as an example.

Laws	Ohm's Law, Kirchhoff's Law, Rules of Arithmetic
Conditions	parallel circuit, resistor values, input voltage
entail	______________________
Explanandum	measured voltages and currents

This provides a better theoretical model for the VL than straight deduction as it allows for the inclusion of conditions. Also, from a pedagogical point of view the explanatory process is more illuminative than deductive inference. We might use this method to describe the apparent structure of this VL. The VL is based on underlying rules which have been derived from a set of rules or laws; the choice of which will be discussed below. In the example, above, these would be related to the calculation of electrical quantities in a circuit. The conditions set are two 10 ohm resistors in a parallel circuit, with a 9 V direct current supply. The observations are a current of 0.9 A and a voltage of 9 V. For Hemple, then, these observations are explained by the combination of laws and conditions, just as they would be in a real experiment.

Realism, positivism, instrumentalism and explanation

The concept of explanation raises the question posed by scientific positivists and realists (O'Hear, 1990, pp. 97-110; Bird, 1998, pp. 121-161; Okasha, 2016, pp. 54-70) concerning unobservable phenomena. The idea of explanation is essential to the VL and in a sense, this is all based on unobservable phenomena – unless you have written the code yourself, it is essentially a 'black box', providing outputs to given inputs. What happens in the black box of the VL is *by its nature* not the same as that which happens in a real laboratory. Our justification for using VL cannot be that it replicates nature in every way, only that given a set of starting condition and rules, the results replicate nature in a limited set of ways. For example, we would not expect the VL to produce the smell of ammonia and feel of a warming test tube during a reaction, but we expect to see a colour change for a litmus paper test.

Realism

The concept of realism is based on the view that there exists one real world. Therefore, there exists a truth which is 'true regardless of what people think' (Hacking, 1981, p. 1). From this comes the basis of much of the scientific method, which relies on the idea of 'unique best description' (ibid).

Positivism

Taking a positivist perspective, means that we are not so concerned with explaining why something occurs in terms of any underlying theory, only the empirical results (Bird, 1998, pp.121-125; O'Hear, 1990, pp. 89-91, 106-110). Positivism comes in a number of forms such as logical positivism (Redman, 1993, 7-11) and anti-realism (Bird, 1998, pp. 124,124; O'Hear, 1990, p. 106-110). A general summery of the positivist position is provided by Hacking (O'Hear, 1990, pp. 106-110) giving six main points about which most positives agree:

1. 'Emphasis on verification and/or falsification'
2. 'Sensory observation founds all genuine knowledge'
3. 'Causation amounts to no more than talk of constant conjunction between types of events'
4. 'A suspicion of the role, and even the possibility, of deep explanations in science'
5. 'Hostility to unobservable or theoretical entities'
6. 'Opposed to metaphysics'

There is considerable debate in the literature over these issues which has rumbled on for centuries (Bird, 1998, pp. 122, 123; Redman, 1993, pp. 3-44) and the alternative 'realist' view. In this thesis I am only going to be able to briefly review the point of the debate relevant to VL, and even then, at a fairly superficial level. Looking at Hacking's list and applying these points to VL, suggests:

1. VL does not provide an opportunity to consider verification/falsification as it is internal consistent.
2. Sensory observation is mediated via the VL.
3. Causation is an inbuilt part of the VL.
4. The explanation of the result of a VL experiment is based on a different process from the physical world: the movement of electrons in response to an algorithm.
5. Theoretical underpinning is an essential part of the operation of the VL.
6. Metaphysics plays no part in the VL.

From this it can be seen that the VL does not fit well with the positivist approach. This is equally true for the realist thesis.

Instrumentalism

Instrumentalism 'regards theories not as attempts to describe or explain the world but as instruments for making predictions' (Bird, 1998, p. 125). From this point of view 'empirical adequacy, not truth, is the real aim of scientific theorizing' (Okasha, 2016). This is a fundamental concept for the VL, in a sense and indeed in reality, the instrument of the VL does not 'explain' the world. Electrons are moved in certain patterns, according to input data and the programming configuration, to produce an output – which the user interprets as a view of reality. At a fundamental level there is no explanation and no direct correlation between the movement of an electron and the physical process being replicated in the VL. Figure 19, shows a schematic of the process, this is identical to that for the VL with 'theory' replaced by the VL program, as shown in Figure 20. This is compared to the case for data processing by a real instrument, shown in Figure 21. As can be seen, all three processes have the same general form, in which the output is a modified form of the input, all of these are modified by the process. In this sense all observations are subject to the nature of the theory which has 'shaped' them.

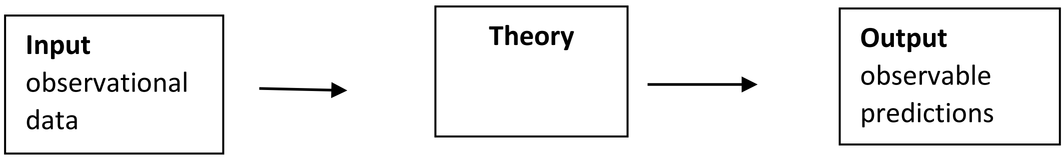

Figure 19 Showing the concept of instrumentalism, from Bird (1998, p. 125)

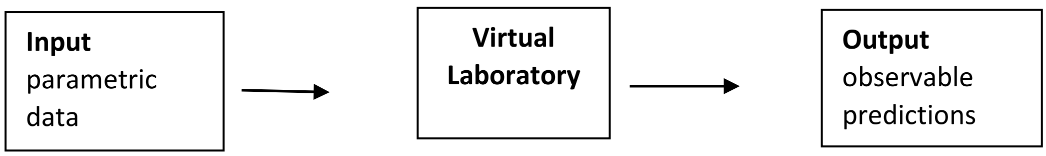

Figure 20 Showing the VL as part of an instrumentalist process.

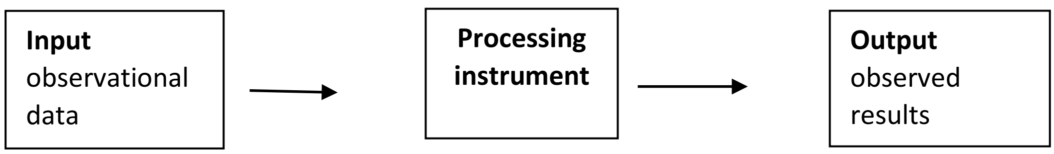

Figure 21 Showing the processing of real data by an instrument.

This type of instrumental process (Figure 21) is common in modern science, where many operators, treat their instruments as 'black boxes', with limited understanding of the electronics inside – I certainly have been guilty of this. So, if instrumentalism is common in the real laboratory, then why is it more of an issue in the VL. This is related to the importance of theory in the process. For the real-world case the observations and processing are often (possibly always) 'theory-laden', as discussed above; this shown in Figure 19. However, it is the emphasis on the different stages which really distinguishes the output. For the real experiment it is the 'real data' which is key, the processing is secondary and could be carried out in many different ways to still produce valid information (provided you know how the data is being manipulated). On the other hand, for the VL it is the processing model which is key, any reasonable input data can produce a result. However, that result will change fundamentally, if the model is altered. The result is only valid if the process inside the black box is appropriate to the task.

This dependence on the correct model to produce valid results means we need to be very careful in our choice of models for a VL. For Box and Draper (1987) 'All models are wrong, but some are useful', so we need to be aware of the limitations of our theories. Cartwright (quoted in O'Hear, 1990, pp. 128-129) cautions that 'in general, nature does not prepare situations to fit the kinds of mathematical models we hanker for. We construct both theories and the objects to which they apply, then match them piecemeal onto real situations, deriving – sometimes with great precision – a bit of what happens, but generally not getting all the facts straight at once. The fundamental laws do not govern reality. What they govern has only the appearance of reality and the appearance is far tidier and more readily regimented than reality itself'. Similarly, Feyerabend (2010, p. 33) suggests that 'no theory ever agrees with all the facts in its domain'. We need to be cautious in the choice of models for the VL and realise that they are an imperfect 'mirror-tool' (Sennett, 2009, p. 84).

Explanations

When it comes to explanations matters are no clearer. For explanations to make sense, there is an implicit reliance on the concept of causality. To explain why A causes B, you must first accept it is possible that A could cause B, not just that A and B both occur. Hanson (1962, p. 94) suggest an 'event is explained when it is traced to other events which require less explanation; when it is shown to be part of an intelligible pattern of events'. This leads to ever decreasing circles until we reach an 'event needing no explanation' (ibid, p. 95), which provide 'the ultimate shackles in chains of physical explanation' (ibid, p. 95). As an example, Hanson considers Newton's laws of motion, the first law is 'All bodies remain either at rest or in uniform rectilinear motion, unless compelled by impressed forces to change their state' (ibid, p. 94). He points out for many 'it tells us what happens in nature', 'it could not but be true' (ibid, p. 96). There is an acceptance of *a priori* truth of the law, based on empirical evidence and the belief that '[w]hatever proves a body's motion not to be rectilinear also proves it is acted on by forces' (ibid, p. 96). Yet it is not possible to properly test the first law as there are no circumstances in which an object is not subject to some force, and even if it were, an 'unknown' force could be postulated. Hanson goes on to explore Newton's second law and determines five distinct interpretations (ibid, pp. 99-100), which lead to different perspectives in different situations. The acceptance of the Newtonian laws is the acceptance of a paradigm (in the sense of Kuhn) it gives a world view and questioning the basis of the laws, changes the paradigm.

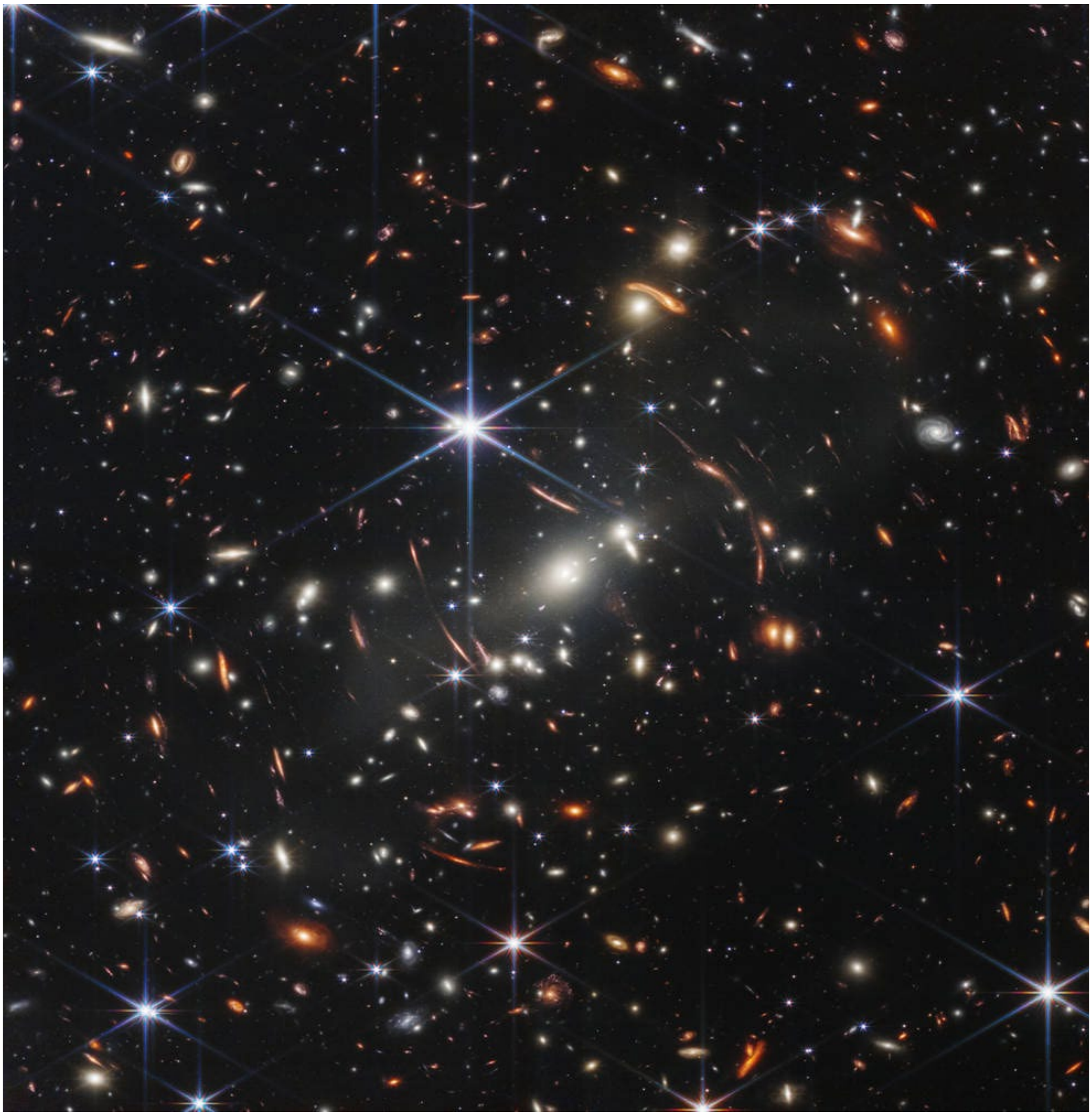

Figure 22 showing the James Webb telescope's First Deep Field infrared image of galaxy cluster SMACS 0723.

Taken from the NASA image given at https://www.nasa.gov/sites/default/files/styles/full_width/public/thumbnails/image/main_image_deep_field_smacs0723-1280.jpg?itok=6-LM40Qf

One of the problems with explanation is illustrated by the Figure 22 showing the recent James Webb telescope infrared image of deep space. The area of the image is equivalent to that covered by a gain of sand held at arm's length on the ground (NASA, 2022). If the image is presented without explanation – it is meaningless – a collection of dots, swirls and smudges. It is the explanation of what it is, that gives it value. However, the explanation is based on layers of technical and scientific knowledge and understanding. Firstly, the image is unique it cannot be checked by another instrument from Earth or space, we do not have another one. Even with great care, artifacts may occur, we cannot check. Secondly, the image was recorded in the infrared so false colour has been used, so we can visualise the patterns; we could never 'really see' this image. Thirdly, the image relies on a range of technical transformations, with processes such as – photons of infrared light are gathered using a complex mirror system, these are detected then transformed into electrical signals, amplified, digitised, accumulated, transformed into radio signal, transferred to Earth, transformed back into electronic signals, processed to produce an image based on a set of algorithms, leading to a visible image. Further the explanation relies on fundamental assumptions about the nature of physics far beyond this planet and back in time over several billion years, these are impossible to check. There are further assumptions about the nature of matter and space time which based on theories which are probably incompatible (see for example, Hanson, 1962, p. 152; O'Hear, 1990, pp. 100-103). Theory is vital to the operation of the VL, as it is to interpreting this image, it is theory which gives the structure for the narrative it is telling. The choice of theory is then a vital step in the process. As we can see from the above discussion there is no one right answer to the question of which theory or theories to use. The choice for VL is discussed further, later. However, the next few sections give some tools which can be employed if not in the choice of the 'best' theory, then the one most appropriate to use in a VL in a given circumstance.

Hypothetico-deductive method

This is the basis of what is sometimes called 'the scientific method'. A hypothesis is generated from observations and is then tested against other data (see Bird, 1998, pp. 91-94). The testing requires that the new theory makes predictions and that these can then be further tested in new experiments. Hanson (1962, p. 70) distinguishes between hypotheses derived by 'induction-by-enumeration' where the data tell a 'story' which frames the hypothesis (HSW 4, 5) and the hypothetico-deductive (H-D) method, in which it is the 'high-level hypotheses' which are used to explain the data (HSW 1). So, either the data explains the hypothesis (induction) or the hypothesis explains the data (deduction). Newton (in O'Hear, 1990, p. 104) says that from experiment, 'particular propositions are inferred from the phenomena and afterwards rendered general by induction.' That is, laws are obtained empirically, the data with 'unobserved causal links' being no more than 'a disguised way of referring to regularities … existing between types of observed event' (ibid, p. 103). However, for H-D the direction of travel gives 'fundamental inference … from higher-order hypotheses to observational statements' (Hanson, 1962, p. 71). We are working towards 'an 'ideal of natural order,' that is, a principle of regularity or paradigm, specifying a 'natural course of event' that scientists regard as self-explanatory or natural.' (Redman, 1993, p. 79). In a sense the VL is a perfect example of this second, deductive, embodiment, the theory is set and all observations flow from it.

Inference to the Best Explanation

Inference to the best explanation (IBE) is the process of choosing the 'best' explanation to explain a certain set of conditions. This is considered by some (Okasha, 2016, p. 24) to be a form of induction, extended to compare different possible hypotheses. This process is described in more detail by Bird (1998, p. 85) and the similar (possibly, the same, process – depending on exact definitions) is explained as 'abduction' by Hanson (1962, pp. 85-86). Hanson also uses the term 'retroduction' (ibid, p. 86) which is a similar form of logic, described by Aristotle as a process by which 'we approach more nearly to knowledge' (ibid, p. 85). Peirce (in Hanson, 1962, p. 85) sums up the different forms of logic as: 'Deduction proves that something *must* be; Induction shows that something is *actually* operative; Abduction merely suggests that something *may be*.'

IBE is widely used in science (Bird, 1998, p.85; Okasha, 2016, p. 24) both implicitly and explicitly in reasoning towards knowledge. The method is used by Darwin, to defend natural selection and Einstein, in the explanation of Brownian motion, in examples cited by Okasha (2016, pp. 24-25). Bird (1998, pp. 86-87) uses examples of the meteorite theory for the extinction of the dinosaurs and the Big Bang theory to show the widespread use of the method. The logic is not conclusive but works on the persuasive argument that – 'It could hardly be supposed that a false theory would explain, in so satisfactory a manner …' (Darwin, in Okasha, 2016, p. 24). However, this still leaves the issue of how to arrive at the 'best' explanation. Simplicity is one criterion which is used – following Ockham's razor – then the explanation which is least complex is the best. However, this makes an implicit assumption about the structure of the Universe and whether just because a theory is less complicated it is a truer reflection of reality is highly questionable (Okasha, 2016, p. 26; Bird, 1998, pp. 89-90).

Cartwright (in Papineau, 1996, pp. 314-325; O'Hear, 1990, p. 129) takes a more nuanced and localised view, rather than looking for the ''best explanation' for something which … need no explanation to begin with'. Expanding the point, she continues a 'theory is successful in its domain' whether the domain is large or small and '[t]heories are successful where they are successful, and that's that'. This view is taken up in the concept of the VL. For a VL we rely on a *localised theory* or explanation which applies inside the VL, but not necessarily elsewhere.

Inquiry

The method of inquiry is strongly associated with the work of Dewey and the pragmatist perspective (Biesta and Barbules, 2003). Dewey (2011, p. 122) takes a positive view of science as a method for gaining knowledge, he cites Spencer stating that 'from all points of view scientific knowledge is the most valuable'. Dewey's view of science, however, is rather that of a process than a fixed body of knowledge. He regards science as the 'outcome of methods of observation, reflection, and testing'; 'both logically and educationally, the perfecting of knowing' (ibid, p. 121). So, for Dewey the important feature of science is the method of inquiry – 'it involves an intelligent and persistent endeavour to revise current beliefs'. The methods are deductive where the 'subject matter is of a nature to exhibit to one who understands it the premises from which it follows and the conclusions to which it points' (ibid, p. 121). Dewey goes further in recognising that the knowledge generated is not neutral but feeds back into the process with the 'outcome of the activity bringing about certain changes in the environment' (ibid, p. 121). Evidence of the value of inquiry-based education is provided by meta studies, such as that by Minner, Levy and Century (2010), who conclude that, '[t]eaching strategies that actively engage students in the learning process through scientific investigations are more likely to increase conceptual understanding'.

Russell (2000, pp. 776, 777) reviews the ideas of Dewey and in particular his model of inquiry as the way of understanding the world. Russell agrees with the main thrust of Dewey's thesis based on 'what is true (or false) is a state of the organism, but it is true (or false), in general, in virtue of the occurrences outside the organism'. Russell takes up this idea and discusses the concepts of 'meaning' and 'significance'. He proposes 'a sentence S 'means' an event E if it promotes behaviour which E would have promoted' (ibid, p. 777), if not the sentence is false. He continues by applying this idea to beliefs which cannot be expressed in words – 'a belief is a state of an organism promoting behaviour such as a certain occurrence would promote if sensibly present; the occurrence which would promote this behaviour is the 'significance' of this belief'. He gives an example of the announcement in a zoo, that 'a lion has just escaped', would have the same effect as seeing the escaped lion – if you believe the announcement you would run away. This is similar to the view of Peirce (quoted in Biesta and Burbules, 2003, p. 6) that 'different beliefs are distinguished by different modes of action to which they give rise'. Applying this to virtual laboratories suggests that if you carry out an experiment and believe the result is 'meaningful', you will respond in the same was as in a real laboratory – you might record the result in a table, note an observation or wonder what effect a change in a parameter might produce. Thus, the VL can be quite limited in its effects to be 'meaningful' – we are operating at the level of the sentence – a single idea, rather than a more holistic view.

However, Dewey's overall view of the VL may not be so positive, he complains of scientific knowledge being 'communicated in a ready made form' (Dewey, 2011, p. 122). He maintains that 'laboratory exercises' do not constitute the 'scientific method' and so would regard the VL as even further from good education. For Dewey, the act of inquiry needs to modify the environment, he sees progress as 'enriching prior purposes and forming new ones' (ibid, p. 123). While, there is some user interaction with the VL, it is fixed in time, at the point of its construction. This may prevent the modification of purpose Dewey is looking for. For Dewey, the VL is likely to be a stale environment unable to provide 'magic' with processes 'disassociated' from 'the materials and processes used out of school' (ibid., p. 121).

Bayes' theorem

Bayes' theorem is a formal method for determining (in principle) how likely a theory is to be correct. The method is discussed by several authors, see for example, O'Hear (1990, pp. 47-49); Bird (1998, pp. 203-213); Salmon (in Papineau, 1996, pp. 256-289); Glymour (in Papineau, 1996, pp. 290-313); Okasha (2016, pp. 33-35). The idea is to provide a probability for the likelihood of a theory being correct, based on those of the test data being correct, given how severely a theory is tested. This relies on the estimation of probabilities based largely on prior knowledge and 'a scientist's 'best guess' about the hypothesis' (Okasha, 2016, p. 35). There are some interesting possibilities for applications of these ideas to VL, but these are beyond the scope of this thesis.

Gestalt

Gestalt theory has already been considered in terms of the ‘Gestalt switch’– a complete reinterpretation of an object from two or more perspectives. This occurs when the user of the VL sees the patterns on a screen, not just as lines, but as laboratory equipment. In this section the principles of Gestalt are considered and how this leads to ‘something such as a structure or experience that, when considered as a whole, has qualities that are more than the total of all its parts’ (Cambridge, 2022). This is the case when we think about a VL, it is clear that the experience of the student viewing the VL is more than the movement of points on a screen. This is true for all visual (and aural experiences), we bring something of ourselves and experiences to interpret these (see the section on observation, in Chapter 2). ‘When we are presented with a number of stimuli we do not as a rule experience ‘a number’ of individual things, this one and that and that. Instead, larger wholes separated from and related to one another are given in experience; their arrangement and division are concrete and definite.’ (Wertheimer, 1923).

Gestalt Principles

There are a number of different interpretations of the Gestalt principles. These are formulated to refer to visual objects but could be extended to other senses. I will use the ones given in Table 15.Common fate is not one of the original six proposed but has been added later.

Table 15 showing a common interpretation of the Gestalt Principles

Figure-ground	The distinction between groups of objects perceived as close to or far away
Similarity	Objects which look similar are grouped together (e.g. colour, size, shape)
Proximity	Objects which are physically close are grouped together
Common fate	Objects which appear to move to in the same way – towards the same end.
Continuity	Objects which appear to be part of a continuing shape (e.g. dots forming a line)
Closure	The apparent completion of an object with the inclusion of missing parts
Symmetry	The need for symmetry or balance

Adapted from Gestalt Principles (List, Definition, and Examples) | Practical Psychology (practicalpie.com)

These principles are useful in the construction and analysis of VL embodiments. The RSC titration screen experiment is assessed in terms of these principles and the analysis shown in Appendix 19.

Gestalt Switch

The concept of the Gestalt switch has been discussed previously, it is examined in some detail by Hanson (1962, pp. 11-19) in relation to observations. He points out that in the image such as Figure 12 we see the same picture each time the same physical lines, but at a point ‘the organisation of what we see changes’ (ibid, p. 12) and we see a completely different image. Hanson (1962, p. 83) likens the switch to that of Kepler from the idea of the libration to elliptical theory and also, particle-wave duality (ibid, pp. 142- 149). In the context of the learners response to a VL, the switch between interpretations can be dramatic, for example, in an anatomical application where the switch is from a life-size representation of a moving body – to a microscopic movement of muscle cells; or from the wiring of a conventional circuit – to electrons flowing in a metal lattice. These switches of perspective require a reorientation of paradigm and it is not always clear that the magnitude of these conceptual changes is considered in VL applications or indeed in science education, generally.

The formation of knowledge

'Epistemology without contact with science becomes an empty scheme. Science without epistemology is—insofar as it is thinkable at all—primitive and muddled' (Einstein, in Howard and Giovanelli, 2019).

In this section I set out more explicitly, my perspective on the nature of knowledge. This is not a fully formed idea, but it is how it seems to me, when I think about what knowledge is. This particularly relevant to VL, for which patterns form a fundamental structure. All inductive logic is essentially pattern recognition and the VL is built on this basis. When our students use a VL they are guided or allowed to wander, through a series of actions. These actions form a pattern, producing a certain result. A different set of actions, a different pattern, leads to a different result. The VL produces a definite pattern, if as suggested below each pattern leads to, or rather is, knowledge; we are building knowledge inductively. In the VL, this is planned, certain, reproducible. This might be very different to a real laboratory where the series of interactions, although planned, is subject to many competing factors. The patterns are not clear, there is not the certainty that one step will lead to the next. The student must pick out the important patterns from an assortment of different stimuli, this requires a different type of logic, deductive, or more likely abductive, to find patterns in the confusion.

Patterns

Patterns could be considered as a basis for human knowledge (see the discussion by Tseng, 2022). When we interact with the world, we tend to fit our experiences into a framework which we have developed throughout our lives. From birth we are faced with an overwhelming input of sensory stimuli. We learn to prioritise these and develop strategies for making sense of the world. One of the main ways we can make sense of our experiences is through the use of patterns. We learn patterns from our experiences of life, night and day; hunger, crying and feeding; daily routines (much advocated in childcare manuals (for example see, Malenfant, 2006)). Our development of language is based on the establishment of patterns based on copying and repetition of sounds. We are taught to sort into colours, shapes, textures, species and all manner of other categories. We are taught to group like things together. We are then taught to order groups e.g. colours of the rainbow, size of animals etc. and to order within the group e.g. shades of red, letters of the alphabet. We establish patterns of language and thought based on these patterns. We develop an appreciation of the sequencing of events -- things happen in a particular order, the days of the week form a particular sequence, this is repeated without break. A second pattern, the days of the month and months in the year runs alongside this first pattern. This is more of an issue, the days and dates do not match, the first day of the month often differs month-to-month. Then months have different lengths, there are leap years, days and dates change from one year to the next: we need a set of rules to predict the changes. We need a set of rules which tells us how the two patterns interact. I may not know the day of the week of my 100th birthday, but I can use these rules to work it out. There are however issues which can cause problems with this ordered view. The first is complexity, the length of the day is defined in terms of the rotation of the Earth, the year in terms of the orbit of the Earth around the Sun, unsurprisingly these do not match neatly, hence the complicated system of leap years. The further into the future the more complex the corrections needed – we lose our simple understandable pattern in complex rules. The second issue is natural uncertainty, the period of rotation of the Earth and orbit of the Sun vary over time; we can predict what might occur based on what we now know, but this adds further complexity and uncertainty. Thirdly, there is the uncertainty of the paradigm shift. Such a shift occurred in the change from the Julian to Gregorian calendars. This occurred in Europe from 1582 onwards and in Britain not until 1782, due to popular resistance. Such as change has the effect posing questions about - what is the fundamental basis of the pattern? Could this happen again?

Returning to the fundamental nature of patterns, we can see that language is based on patterns which are linked to how we think. We construct meaning from language based on patterns. There are numerous examples on the internet of text where all the vowels have been removed from the words in a sentence, which remains intelligible- 'ths sntnc hs th vwls rmvd'. We can recognise underlying patterns.

Illusion provides an interesting example of the underlying effect of pattern recognition. Examples such as Rubin's vase (face / vase) illusion have been shown by fMRI to stimulate different areas of the brain (Wang et al., 2017). This suggests that brain architecture may affect the structure of the patterns used in recognition. Hanson (1962) recognises this separation of recognition when discussing how objects are viewed by different observers. This is particularly relevant to the understanding of the progress of science since Kuhn (1996) lays considerable emphasis on this 'Gestalt switch' as a model for paradigm change. If indeed, the paradigm shift is similar to the Gestalt switch, then this would strongly support Kuhn's claim of the incommensurability such ideas – with different ideas located in different areas of the brain. I would expect that ideas which are merely incompatible would have to be dealt with in the same space, as a comparison is required to establish incompatibility. Whereas, incommensurable paradigms might well effect different areas as they are constructed on completely different bases.

The effect of the 'Gestalt switch' on the nature of observation is explored, in some detail, by Hanson

> *A model calculation*
> So, we could now consider the calculation of the day / date problems as a simple analogy for the complexities which might be encountered in the VL. First, we have a simple pattern – days of the week then we introduce a second pattern, the days of the month, which interacts. We can establish a set of rules for these, one simple and one more complex. Both can be described mathematically, so we can develop a algorithms to calculate the result and produce a model which will provide us with the day / date match. But now we need to be aware of the limitations of the model – without understanding the underlying issues and assumptions we do not know how much credence we can put in the result.

(1962, p. 11). He considers 'do I really see something different each time, or do I only interpret what I see in a different way?' and claims that 'One does not think of anything special; one does not think at all. Nor does one interpret. One just sees, …' (Hanson, 1962, p. 11). Hanson explores the idea of Tycho Brahe and Johannes Kepler, watching the sunrise, do they 'see the same thing in the east at dawn?' Hanson explores this question as 'the beginning of an examination of concepts of seeing and observing'. Here again we see relevance to the VL, does one student see the same thing as another? Their prior experiences will inform their observation, how can they interpret the pattern of lines on the screen as a volumetric flask if they have not already seen one? Or if a 2-dimensional image is presented as a burette, do they, like Plato's prisoners, struggle to conceive of it as three-dimensional glassware? Is there a point for some, staring at the computer where a Gestalt switch occurs, they no longer see lines, but a 3-dimensional object?

Similarly, the idea of schema for organising information proposed by Bartlett (Brewer and Nakamura, 1984) could also be seen as being based on underlying patterns. These schemata provide a structure into which new ideas can be fitted. This is similar to the process of identifying knowledge in relation to patterns which already exist within the mind. This can also be seen in terms of the Gestalt principles, discussed above, with the idea of Continuity (of a series), this is explored below.

Knowledge as patterns

One way we understand the world is to look for patterns. We create meaning from patterns. The more often we see a pattern the more confident we are of the reality of that pattern, and this becomes *knowledge*. For example, we 'know' that the Sun will rise every day, because it is a pattern which is part of *our* nature. We know because of experience and experience creates patterns in our minds. It is these patterns which we then use to interpret new experiences and to build 'facts'. This idea can suggest how misconceptions arise and how two people looking at the same data can reach very different results; it also suggests a mechanism for describing higher order thinking.

It is easiest for me to use a mathematical example, as I have been educated as a scientist – so I often think in numerical patterns (and as the VL is built on mathematical algorithms it has intrinsic patterns). So, we have a group of numbers – what do they mean? I could start by sorting them into groups to see if there is a pattern – are they all even? Or multiples of 3? Or prime? The groups I try to use are based on my experiences – my innate belief in what constitutes an important characteristic. I might then try to order the numbers: naturally, *I,* would choose to order in increasing or decreasing value, but that is because these patterns are part of *my* thinking. Say I have the numbers:

100, 102, 104, 106, 108

These to me are even numbers 100 or greater – I would expect the next number to be 110. But maybe to you they are the even numbers below 108, the series goes the other way and is preceded by 98. (see Wertheimer, 1923).

What about: 24, 30, 36, 42; these are even and multiples of 3 – that means they are also multiples of 6 – which is the most important? If I have only been taught about even numbers – then to *me,* they are clearly a set of even numbers and I might look to fill in the gaps – I would want to add in 26, 28 etc. However, if I have only experience of multiples of 3 then I am looking for 27 and 33. If I know about the 2 and the 3 times tables, I might be able to build new knowledge as I can see a pattern based on 6 developing. If we 'understand' the pattern, then we can extend it (induction). It can be seen that the pattern which we are expecting will now influence our interaction with new data and the development of new knowledge. The number 48 will confirm the beliefs of those looking for evens, multiples of 3 and the addition of 6: all the rules are obeyed.

If we now have a set of numbers 24, 25, 30, 35, 36, 40, 42, 45 then this no longer obeys our previous rules; however, if we analyse this further in terms of patterns, we can see our original pattern of multiples of 6 and another of multiples of 5 combined. It is only if we can recognise both patterns that the overall sequence will make sense. We analyse in terms of the patterns which make sense to us.

An analogy is a square filled with apparently random numbers. Using our knowledge-patterns to filter type and range of patterns that might exist., e.g. primes, spaced by 3, or odds spaced by 3, we identify possibilities. Prior knowledge say – a familiarity with the times tables or primes, might improve the analysis. We then show wisdom in the ability to choose the most appropriate patterns to explain the data. Thus, wisdom is context dependent and relies on the patterns we already know. For the VL it is necessary that learners recognise the patterns on the screen as objects in the laboratory, they need to make the link based on the patterns they already hold in their minds. For example, the pattern of lines which they recognise as a beaker, can only be recognised because they have already a mental pattern for a beaker, because they have seen one before or it has been described to them.

These ideas suggest that patterns can thought of as units of knowledge. Each observation, fact or skill is characterised by a number of elements which forms a group. This group is then compared to the inherent patterns we hold for different entities. If we believe there is a sufficiently close match with this predetermined pattern – we associate the two and recognise the group as that entity. This can lead to new learning or new misconceptions in two ways: we might modify our preconceived pattern to fit more closely to our observations or modify our perceived observations to fit more closely to our preconceived pattern. So, we may be mapping the entity onto our preconceived pattern, not the actual elements of the observed group. It is now the schema we have, that stands for the observation; we do not retain all the individual elements of the observation. This is why conjuring tricks are so powerful. For example, of Bruner and Postman's study, described by Kuhn (1996, pp. 62-64) used modified playing cards to investigate observations and found these were 'fitted to one of the conceptual categories prepared by prior experience' (ibid., p. 63) (We see the beaker because we have experienced beakers before). This suggest that learning can be regarded as the modification of an existing schema or tacit pattern; or its replacement by a new one. Teaching then becomes the act of facilitating this change and directing the formation of new schema towards a better representation of reality (or some other learning objective).

Bloom and patterns

The concept of patterns can be further examined through the lens of Bloom's taxonomy (UArk, 2013). In Chapter 2 the possible relationship between practical science and VL were considered in Table 5 and Table 6. In Table 16 Bloom's taxonomy is described by reference to patterns, with the building up through level descriptors. The form of this building up towards complexity is similar to that described in Table 6 for the VL and opposite to that for practical science shown in . This would suggest that the pattern-based nature of VL is a better match to learning based on Bloom's analysis.

Table 16 showing the relationship between Bloom's Taxonomy (UArk, 2013) and patterns.

	Bloom's Taxonomy (UArk,2013)	Patterns
Knowledge	Retrieving, recognizing, and recalling relevant knowledge from long-term memory.	Observing and recognising patterns. Comparing patterns to ones which are already familiar.
Understanding	Constructing meaning from oral, written, and graphic messages through interpreting, exemplifying, classifying, summarizing, inferring, comparing, and explaining.	Describing patterns, identifying their important features. Elucidating the general form of the pattern.
Applying	Carrying out or using a procedure for executing or implementing.	Modelling patterns. Do the patterns exist in other contexts?
Analysing	Breaking material into constituent parts, determining how the parts relate to one another and to an overall structure or purpose through differentiating, organizing, and attributing.	Analysing the possible models of patterns, comparing to reality. Identifying the relative importance of multiple patterns.
Evaluating	Making judgments based on criteria and standards through checking and critiquing.	Judging the goodness of fit to the data and the relevance of different models
Creating	Putting elements together to form a coherent or functional whole; reorganizing elements into a new pattern or structure through generating, planning, or producing.	Extending and refining models

Kinds of Knowledge

Russell (1948, p. 439) suggests there are two kinds of knowledge: ‘first, knowledge of facts; second, knowledge of the general connections between facts’. Both of these are easily expressed as patterns and so can be expressed within the VL. The ‘fact’ is a pattern, which can be explicitly recognised, for example, a table or a beaker, the essential features of each can be expressed in the VL by series of lines. The second the relationship between the two – we ‘know’ the beaker will rest on the table (and not pass though it), this is the expected pattern of behaviour, which again can be replicated in the VL.

Russell (ibid) also suggests an alternative distinction based on ‘mirroring’ knowledge and that which has a ‘capacity to handle’. Mirroring knowledge is like memory, fixed, a pattern which even if imperfect, is essentially unchanging. The VL provides a range of fixed memories, reproducible patterns. The second is active knowledge the concept of pragmatism: ‘The question whether objective truth belongs to human thinking is not a question of theory, but a practical question. The truth, i.e. the reality and power, of thought must be demonstrated in practice’ (Marx, in ibid, pp. 439, 440). This is the formation or realisation of patterns from amongst a range of possible patterns. In the real laboratory the range of patterns is unbounded, but in the VL the patterns and therefore the ‘truth’ is built into the structure of the VL. These distinctions are reminiscent of Sennett’s mirror-tools (2009, pp. 84, 85) of replicant (the fixed pattern) and robot (an active pattern).

The recent paper by Tseng (2022) develops a similar model, to that of Russel (1948), described as the EApc framework. This divides knowledge into: ‘(1) basic knowledge and (2) compound knowledge, where basic knowledge is discovered and compound knowledge is synthesized from basic knowledge’. Basic knowledge is then divided into:

‘Entity: An object, physical or mental.

Property: Attributes of an entity.

Action: A process (physical or mental) required to change an entity or its property.

Condition: Attributes of an action.’

(Tseng, 2022)

Each of these can be linked to practical science and patterns. Thus, an entity is a physical or virtual object is recognised as a pattern of lines and shapes, which in the real or virtual world can be viewed as a particular object. To each object are attached properties which describe the relationships of the entity to the world in which it exists. In the VL these would be the patterns of behaviour of the entity when it is subjected to an action. The action is the stimulus acting on the entity, this can be described in the VL by a pattern or series of changes which is programmed to occur as a consequence of an action. For example, pushing an object across the table will result in the coordinates of each part of the entity changing by a fixed amount. Each coordinate will be modified by a known amount in a predictable pattern: we know what will happen. If the condition of the action is then modified, say the entity is pushed harder, it will move faster, the pattern of coordinates is changed and the object in the VL appears to move more quickly.

Tseng (ibid) then describes ‘compound knowledge [as comprising] multiple entities and actions that are linked together based on their properties and conditions’; this is the complex interaction of patterns which in the VL produces a complex response. This relies on the concept of cause producing action, assuming ‘that cause-effect relation is ‘‘the cement of universe’’’ (MacKay, quote in ibid). Tseng (ibid) maintains that ‘compound knowledge structures can be developed with virtually no limit in variety, dimension, and complexity, as long as enough number of different entities and actions are involved’. However, with increasing complexity it is not clear that actions and their effects on entities can be neatly separated and individualised. This is similar to the issues in perturbation theory, where the Hamiltonian functions need to commute. So, at this level there may be issues with unpredictable interactions between patterns which cannot be truly separated, so cannot be reliably reproduced in the VL.

Dewey’s view of transactional knowledge can also be expressed through patterns. Biesta and Burbules (2003, p. 94) describe this as ‘the transaction with the environment becomes more structured; it is no longer that we shift from one unique immediate experience to the next – we start to recognize pattern, structure, and form’. Thus, for Dewey (quoted in ibid, p. 95) knowledge is constructed through transactions, so ‘any instrument which is to operate effectively in existence must take account of what exists... . But ‘taking account of’ . . . is something quite different from literal conformity to what is already in being’. This grounds our experience in the transaction, so ‘the objects of knowledge have to be constructed out of available “materials.”’ (ibid, p. 95). The VL provides the ‘available materials’, in the form of patterns on a screen from which the user constructs their unique version of the VL through the transactions which they experience.

Tacit knowledge

An alternative way of looking at knowledge has been proposed by Polanyi (Redman, 1993); he envisages two distinct forms of knowledge: explicit and tacit. Explicit knowledge can be expressed and explained, ‘knowledge is information or instructions that can be formulated in words or symbols’ (MacKenzie and Spinardi, 1995, p. 45). These are patterns which can be demonstrated, like a series of words or numbers. However, tacit or implicit knowledge is held within an individual, it ‘has not been (and perhaps cannot be) formulated explicitly and, therefore, cannot effectively be stored or transferred entirely by impersonal means’ (ibid) and as Sennett (2009, p. 78) points out, when that individual ‘dies, all clues, moves, and insights… cannot be reconstructed’. Similarly, MacKenzie and Spinardi (1995, p. 44) emphasise ‘the local, situated, person-specific, private, and noncumulative aspects of scientific knowledge’. Tacit knowledge will then be held in internal patterns, such as muscle memory, a repeated pattern, ‘understanding from repetitive, instructive, hands-on learning’ (Sennett, 2009, p. 39). Sennett (2009, p. 40) sees that a process ‘becomes ingrained in the mind’; a pattern is formed. Sennett (2009 p. 44) expands this point describing the ‘circular fashion’ which builds ‘embodied knowledge’; however, ‘when the head and hand are separate, it is the head that suffers’. This type of knowledge is held in patterns within the individual, perhaps in the formation of physical structures within the brain or other parts of that individual.

The VL is an inherently patterned structure, unlike the real laboratory, everything within the VL can be mapped back to an algorithm – to a pattern. The VL is an explicit structure, the programmer has put explicit knowledge in the form of scientific laws and observations into something which exists independent of them. This suggest that the learning in the VL will be those explicit patterns expressed in using the programs. However, as Sennett suggests, repetition will build deeper skills (and therefore tacit knowledge); and since the skills built in the VL are constructed from a structure with a natural pattern, then this learning might be more successful.

Incommensurability of Patterns

In this section I give an example of how patterns might work explicitly in the process of learning. If I have a set of counters as shown in Table 17, and ask the question what is the number and colour of the next counter? I would expect 35 and violet. But what if this choice is not available? – only, say, 37 and violet; or 35 and brown. This is an issue of incommensurability, I either have a set of numbers or colours, but not both. The problem cannot be solved without a choice between one pattern and another. This is a Gestalt switch, I either choose – number or colour, rabbit or bird, old lady or young – it cannot be both. And yet until the next step – the new discovery – it is both. For six counters there is no conflict – they agree. Those who see colours and those who count numbers agree – the order is the same – all is well. There is a settled paradigm. Emeralds are green and grue. But the seventh step breaks the pattern – one or other or perhaps both, if there is another unseen pattern.

Table 17 showing a set of counters each numbered and coloured, as in the Table.

5	10	15	20	25	30	?
Red	Orange	Yellow	Green	Blue	Indigo	?

This leads onto the problem of misconception. I see the pattern of numbers, my students the pattern of colours, we are happy, we agree we both understand the order of the first six counters, we both have the same knowledge. If counter 3 were missing, we would both agree which one to place there – 15 Yellow. However, both of us would be surprised by the others choice to continue the series (my 35 Brown; their 37 Violet) – it literally would not make sense. Because on this issue we have a different world view. And there will be that moment – the Gestalt switch where we see it the other way and soon for the student will see 35, then 40, 45, 50… they will wonder why colours ever mattered to them at all – they will have accepted the new paradigm. The switch back is impossible – the world will have changed (see Kuhn, 1996).

This idea also helps illuminate the problem of induction. Induction is based on patterns; mathematical proof by induction relies on a series which a can be expressed as a function for a general term of the series e.g. each term is related by adding 2. Induction works for each series, the problem of applying induction now becomes knowing which series is important. In principle, if we define a general enough series, in a deterministic Universe then induction would be guaranteed. From an educational view point we only need the series to be general enough to cover all possible scenarios a student may encounter. For VL the series (or the functions expressing them) only need to be general enough to express the 'realistic' outcome of any experiment. Thus, the process of understanding and gaining knowledge suggested in this section, suggest that the VL needs to use algorithms which are consistent with reality only as far as is needed to produce a 'realistic' outcome in the limited environment (see Cartwright, in Papineau, 1996, pp. 314-325; O'Hear, 1990, p. 129) of the content to be learnt: the VL need not be generally true.

Finding Patterns in this Study

Considering a separate but related point; as part of the data analysis for this study I will be attempting to find patterns. If knowledge is held in patterns, the grouping, selecting and ordering of the data should help to reveal this. I will try to identify not only the explicit patterns of behaviour in the VL, but also how these allow knowledge to be generated for each student. Each will develop their own implicit set of patterns based on their experience in the VL and their prior experiences. Some of these will be made explicit in their choices and comments. Using a technique, such as thematic analysis (discussed below), I am hoping to explore the common patterns which are experienced in real and virtual laboratories. If clear patterns emerge, these will identify new knowledge and learning for the students.

Ethics

The philosophical topic of ethics is generally concerned with the concepts of right and wrong, and how one should act. There are three main ethical perspectives; one which emphasizes the following of rules and duties, a second concerned with the consequences of any actions and a third concerned with values and moral character (Hursthouse and Pettigrove, 2022). Although this thesis is not really concerned with ethical issues, there are some issues worth highlighting here. First there are ethical issues concerned with the conduct of this study which are addressed below. Secondly, there the general ethical issues surrounding education (see for example, Gajewski, 2017; Bagnall and Hodge, 2022) which are beyond the scope of this thesis. A third area, which does have a bearing on this work is concerned with the choices made in using VL, both in general and as a particular embodiment. When I choose to teach using VL, I am making an ethical judgement, within all three of the perspectives given above. Firstly, I am recognising my contractual obligations and professional standards which direct me to deliver the curriculum, and my judgement that VL helps achieve this. Secondly, that by using VL students will learn science in at least as favourable way of doing this as any other method. Zakaria (2007) studying the use of VL notes, 'teacher … attitudes toward the subject matter and its effective presentation in the classroom can be as significant as the learners' perspectives in determining the success of a teaching / learning experience'. Thirdly, that the values expressed in the VL are consistent with those I want to pass on. By this I mean that the underlying theories are consistent with those I would wish my students to experience and that where necessary they are explicitly stated. While this issue is more likely to occur in the medical or biological sciences, even in physics, the choice of teaching with a geocentric or heliocentric model of the solar system might still be a religious concern (see for example, Faulkner, 2020); this is an area beyond the scope of this thesis.

Another ethical issue which it is worth highlighting for future consideration is the concept of phronesis or 'practical wisdom' (Costello, 2018). 'In Aristotle's words phronesis is a ''true state, reasoned, and capable of action with regard to things that are good or bad for man.'' Phronesis goes beyond both analytical, scientific knowledge (episteme) and technical knowledge or know-how (techne) and involves judgments and decisions made in the manner of a virtuoso social and political actor' (Flyvbjerg in Costello, 2018, p. 3). This is very relevant to practical science and in particular VL where the student is involved in a complex environment in which action based on decisions is required often without a full comprehension of the whole. This is the knub of the research questions set out below. Each is about a judgement and action based on that judgement.

Sophistication and Control

Two areas (sophistication and control) related to ethics, theory-laden observation and causality are discussed briefly next, these are signposted as areas for further consideration but are largely beyond the scope of this thesis.

Sophistication

As systems become more sophisticated it becomes impossible to have a comprehensive view of all the factors involved. Human knowledge is too wide and too deep for any individual to span. This is probably even more the case in the digital world than the real one. Computers are able to perform calculations in seconds which it might take a human a lifetime to reproduce. This means that in a sense we have to believe the computer is right – we cannot check the calculations ourselves. The best we can do is to use other computers to reproduce the same or similar calculations. Sometimes we can compare the results to reality, but for many experiments the results are derived through computer-based analysis of data which cannot be interpreted by simply looking at it. So, for many aspects of modern science, including the VL, there has to be a level of belief in the process.

Sophistication results in further problems in the complexity of the interacting algorithms used in both real and virtual laboratories. Many results rely on a complex interaction of different programs, each of which is based on a set of theoretical principles. There is often no guarantee that the concept underpinning one program is compatible with that used in others involved in the process of producing the result.

Gibbons (2016) describes sources of errors in computer programs and suggest that there are significant problems in replication of results for many modelling programs (these are the basis of any VL). He describes how sophisticated code mean 'that these models can be nearly impossible to reproduce' thus 'an important touchstone of science is being challenged': one of the basic tenets of the 'scientific method' is the ability to replicate results. Of course, errors can also occur in the real laboratory both in making measurements and in the underlying assumptions on which these have been made. Kuhn (1996, pp. 62-64) cites the experiment of Bruner and Postman to show that we see what we expect to see, if it fits with prior experience, and only when the anomaly becomes too great do we accept there is an issue.

While, in the VL we can be certain about the values we measure but cannot be certain about the process, in any but the simplest representations. So, what happens when the computer values and reality do not match? There are numerous examples where errors in input data or calculation have real world consequences; for example, errors in financial calculations by the Horizon IT system (HuffPost, 2022) led to the criminal conviction of over 700 sub-postmasters, because no one would accept that there were errors in the computer calculations. This is an issue with any sophisticated system for which it is not possible for a single individual to comprehend all parts of the process.

Control

Following on from the above example of the Horizon IT system there is a question of control. Who operates the system, who monitors whether the program operates correctly, and probably more fundamentally who decides the 'rules of the game'? This will be discussed further below. Here I just want to highlight the importance of the scientific and educational paradigms in crafting the final results.

The VL is synthesised from a range of elements, each of which are selected from a palette. That process will determine the final results and therefore the ‘reality’ for the user of the VL. There are then many layers which affect the choices, not only scientific and educational considerations, but also concerning operating systems, available software licences, costs, timescales, funding, customers, programmers’ skills, and a host of incidental factors. So, the question of who chooses the curriculum / paradigm – scientists, teachers, politicians, exam boards, commercial companies, programmers – is important. The basis on which these choices are made are related to the underlying perceptions of the of those making the choices. Ultimately, this is a matter of philosophy.

A number of books and films explore the idea of who controls reality, in 1984 (Orwell, 1961) the state is able to control peoples’ thoughts, making them believe in a war which may not have existed. In 2001: A space Odyssey, the HAL 9000 computer manipulates reality, and, in The Matrix, an entire world is created, reminiscent of Descartes problem of the evil demon (Warburton, 2001, p. 49-50). In a VL we are conscious that reality may not be exactly reproduced, but we are still in a created world, purporting to be a ‘mirror of reality’. This will become more important as we move towards more and more sophisticated representations; and even more significant as VR become a more common tool. (for example, my college is now using VR as a routine teaching method for Health and Social Care).

In a recent paper, Vasser and Aru (2020) suggest that ‘the ultimate aim of a VR system is to technologically immerse the user into virtual worlds, inducing a sense of presence — the illusion of being in the virtual world and behaving accordingly’. This reminiscent of Russell’s (2000, p. 777) comments on significance discussed above. Furthermore, Chalmers (2023) cautions that we must be conscious of the challenges of VR, ‘including the challenge of a corporation-dominated metaverse where corporations serve as the all-powerful and all-knowing gods who create the virtual worlds’. Chalmers (2022, p. 14) also argues that ‘‘Virtual reality’ is sometimes taken to mean ‘fake reality.’ … Instead it means something closer to ‘digital reality’.’ This idea is beyond the scope of this work, beyond perhaps that of any work it speaks to the issue of what is right and true, as Pilate asked, ‘What is truth’ (St. John, 18:38).

Aesthetics

Aesthetics is concerned with beauty or value (Shelley, 2022). These may be considered either in terms of individual taste or using a ‘disinterested’ rational formalism. In either case, there is a good deal of disagreement (ibid) as to the application of these criteria. Shelley (2022) suggests that, following the ideas of Kant, the modern use of the term aesthetic is close to that of ‘taste’, holding the ‘judgment of beauty to be immediate’. Alternatively, the disinterested judgement of beauty, based more on its value (something which can be more objectively determined).

Hutcheson (quoted in ibid.) suggest that both mathematical and scientific theories could be objects of taste. While Einstein has ‘deep faith that the principle of the universe will be beautiful and simple’ (Quotes.net, 2023), in contrast, Dawkins (1991, p. 6) talks of ‘the complexity and beauty of biological design’. Clearly, beauty can be both simple and complex. It seems to me that physics searches for elegance in simplicity, while biology delights in many levels of complexity. This can be seen in the different versions of VL, with both simple animations and the complex virtual reality laboratories available. It is interesting to ask (but beyond the scope of this work) if the students find the different types of VL more or less beautiful and whether that affects their engagement or learning? Also, if those studying physics prefer simple elegance and those concentrating on biology deeper complexity?

Summary

This first part of Chapter 3 has explored the three main areas of Greek philosophy: Ontology, Epistemology and Value Judgments (Ethics, Aesthetics). Ontology has two main traditions – realist and constructivist. Realists hold that reality is 'reductionist and deterministic' (Waring, 2012 p. 18) while, constructivists suggest that reality is constructed in the mind; based on the theories and experiences of the observer.

Epistemology is 'concerned with what the criteria are that allow distinctions between 'knowledge' and 'non-knowledge 'to be made' (Usher, 1996, p. 11). The realist or positivist tradition endeavour to 'discover' facts which are the basis of knowledge, using the methods of experimental science. Knowledge is developed though hypothesis and theory based on empirical experimentation and observation. The alternative interpretative approaches do not 'see direct knowledge as possible; it is the accounts and observations of the world that provide indirect indications of phenomena' (Waring, 2012, p. 16).

If knowledge is developed through theory, then the choice of theory can affect the knowledge that is gained – this is particularly relevant to VL. Knowledge can be obtained by the logical interpretation of observations through theories. There are different ways to determine the value or truth of a theory, these are discussed and compared. The methods of deduction, induction, explanation, hypothetical-deductive, inference to the best explanation, inquiry, Bayes, Gestalt theories have been considered as well as the perspectives of realism, positivism and instrumentalism. The ideas of Ethics, Aesthetics, sophistication and control have been briefly reviewed.

PART 2: METHODOLOGY

‘I fully agree … about the significance and educational value of methodology as well as history and philosophy of science’ (Einstein, in Howard and Giovanelli, 2019)

Introduction

Methodology is about why we study a problem in the way we do. The scientific method discussed in Chapter 2 is often held up as the pinnacle of truth. This Russell (2000, p. 789) sees as ‘scientific truthfulness, by which I mean the habit of basing our beliefs upon observations and inferences as impersonal, and as much divested of local and temperamental bias, as is possible for human beings’. However, as we have seen the scientific method may not be perfect and it is certainly not suited to all problems. Based on the positivist viewpoint, the search is for an objective truth: there is an underlaying assumption of a truth to be discovered. However, Feyerabend (2010, p. 253) holds a very different view and that ‘‘scientific’ knowledge is in some way particularly positive and free from differences of opinion is nothing but a chimaera’.

The VL itself is based on a positivist premise and science education in the UK is based on ‘the use of conceptual models and theories to make sense of the observed diversity of natural phenomena [and] the assumption that every effect has one or more cause’ (DfE, 2014). However, the positivist perspective is less appropriate to the study of learners’ experience, which is difficult to quantify, and where we are looking for underlying explanations (see Positivist (3, 4), above). For Connelly and Clandinin (1990) it is the ‘study of narrative [which] is the study of the ways humans experience the world’. While van Maanen (2011, p. 64) exploring the value of ethnography suggests ‘Authority rests largely on the unexplicated experience of the author in the setting and the ‘feel’ he has apparently developed for the time, place, and people’. While Carr (1995, p. 83) argues for ‘a view of educational research which is ‘interpretive’ in the sense that its theories are grounded in the perspectives of educational practice and ‘scientific’ in the sense that these theories provide a coherent challenge to the interpretations which practitioners actually employ’. Derived from these perspectives are methodologies which describe how we should proceed in the process of research. Waring (2012, p. 16) says that ‘methodology asks ‘what procedures or logic should be followed?’’ This gives a steer to what might be expected as a focus for investigation during research. The next sections consider different approaches to gaining knowledge in the context of a research study; firstly, the positivist approach is briefly presented before moving on to discussion of the interpretive view which underpins the work presented in this thesis.

Positivist

Positivists would favour the deductive logic, working from general laws to investigate particular cases. This is the driver for Popper’s theory of ‘falsification’ (see Chapter 2). However, there is little ‘real world’ evidence that deductive logic can be applied to non-trivial problems. As O’Hear (1990, p. 27) puts it ‘the conclusion cannot go significantly beyond the premisses’ – a deductive process can tell you little more than you already know. The methods appropriate to this perspective rely on ‘presuppositionless observation’ of an ‘objective observer’.

Interpretivism

The interpretivist is interested in the interactions with, and between, participants in a study. They do not 'see direct knowledge as possible; it is the accounts and observations of the world that provide indirect indications of phenomena and thus knowledge is developed through a process of interpretation' (Waring, 2012, p. 16). The methodology is not designed to give the 'right answer' – which does not exist in this world view, but as Waring (2012, p. 18) puts it 'to distil a more sophisticated and informed consensus construction'. This approach is a form of idiographic research describe by Coe (2012, p. 10) which 'aims to describe and understand what is unique and distinctive about a particular context, case or individual'. The research is then carried out using methods such as focus groups or interviews.

The interpretative approach relies on inductive logic, which has been described above. However, the work of van Maanen (2011) and Connelly and Clandinin (1990), gives a variation on the way of using this approach, by concentrating on verisimilitude. Talking of ethnography, van Maanen (2011, p. xv) says we should consider not only 'the overrated criteria of reliability and validity [but also] the underrated criteria of apparency and verisimilitude'. While for narrative explorations Connelly and Clandinin (1990) suggest that 'like other qualitative methods, narrative relies on criteria other than validity, reliability, and generalizability… We think a variety of criteria, some appropriate to some circumstances and some to others, will eventually be the agreed-upon norm ... We have already identified apparency, verisimilitude, and transferability as possible criteria'. Interestingly, it was 'failures in verisimilitude' which led Kuhn (1996, p. vii) to re-think the progress of science. Moreover, Popper (1976) provides a mathematical definition of verisimilitude based on the comparison of two competing theories. He identifies two features: the logical strength of each; and their critical discussion, including the results of testing; as a way of determining their relative verisimilitude.

This study takes a broadly interpretive approach and although the data obtained in this way is not quantitative or able to prove a theory, it is enlightening and provides a way of illustrating important features in the process of education. The interactions between myself (researcher) and my students (research subjects) are able to throw light on how practical science and particularly VL influences students' thinking. By analysing these interactions, it may be possible to move towards a better understanding of students learning in the VL. As Coffield (2009, p. 62) points out 'Consulting students is the essential first stage of a process which could then lead on to not just treating them as consultants but as trusted fellow researchers into L&T' (Learning and Teaching).

So, for me, the interpretive perspective would seem to offer the best chance of describing the complexity of the experiences that students have in practical science. While their learning can, in principle, be measured quantitatively through tests and exams, this is difficult to achieve for *experience*. In order to measure in a quantitative fashion any questions would need to be predetermined, with a limited range of responses. This is hardly the presuppositionless conditions sort in a positivist approach. It is only though the flexibility of qualitative interactions that I could hope to reduce the effects of my predetermined ideas. Even so, in the sections below I have tried to show how my own perspective and expectations might still colour my results.

Practitioner Research

This study is an example of practitioner research, in that I am carrying out the study from within the entity which is being studied. I as a researcher am part of the story, so cannot hope to be fully objective. The best I can hope for is to set out my views and, as fairly as possible, report my findings of the research. It is important to provide as much of a narrative as possible, to place the study in context; so, allow others to appreciate its relevance.

Gregson (2020, p. 7) describes the process of practitioner research as 'testing out ideas from research and literature in the arena of practice; in attempting to improve that aspect of practice in context; and in interpreting findings … in the light of evidence'. Gregson (2020) goes on to describe the Practitioner Research Programme (PRP), of which this study is part. The PRP has provided a framework in which this work has been developed. Through a system of workshops and tutorials the PRP, focuses on developing methodologies which are 'essentially pragmatic and interpretive' (ibid, p. 7). These 'workshops involve engagement with educational research and literature surrounding a range of issues including, paradigms in educational research, research methodology and research methods in education' (ibid, p. 5). This provides a 'model of educational change and improvement, [that is] an alternative to 'top down' and 'outside in' models of educational reform' (ibid, p. 5). By being located in practice, this form of research leads to 'discussion of enduring issues in educational practice and debates surrounding the nature of knowledge and the processes of knowledge and practice development' (ibid, p. 5). I hope that this work contributes to these aims.

Although the study is inevitably subjective, without a control group or many of the other features of the scientific method, the results can still be useful. This is for two main reasons, the first, is that as an 'insider' I have privileged access to the students, as in an ethnographic study, I am part of the students' daily experience of science, and more than that I am part of the narrative, a fundamental element of the whole story. Perhaps in a sense I am researching myself and how I affect a small portion of the world. The second is that by the application of a methodology, such as that suggested by Nowell et al (2017) and Lincoln and Guba (1985), I can ensure that certain criteria are met, which demonstrate the value of the results. The steps taken in this study to ensure 'trustworthiness' are set out below and in Chapter 4.

There is a relationship between practitioner research and what has been described as 'action research' (see Hammond, 2013; Munn-Giddlings, 2016). Hammond (2013, p. 604) states that 'practitioner accounts of action research … are often focused on more immediate problems of practice and appear practical or technical in scope'. Hien (2009) gives a number of definitions of action research, one due to Creswell is particularly relevant to this study – 'action research aims at addressing an actual problem in a specific education setting namely the teacher researchers are studying a practical issue that will benefit education' (ibid, p. 100). Moreover, 'teacher researchers engage in action research first and foremost because of their own situation rather than someone else's practice' (ibid). Hien concludes that the key feature of action research is that change must occur and that 'change must take place quickly or holistically' (ibid). One aim of my study is to facilitate the implementation VL, Hien would expect the study to produce rapid and comprehensive change – this may be my aim, but I wait to see what will happen.

Research in Educational Contexts

Education is confined in time and space. Traditionally, schools and colleges have operated within ridged controls. Students are expected to be at a certain place, at a certain time. Normally, for a period of time, may be an hour or an hour and a half, a student is expected to be in one room. The students' progress mapped across the day – down even to the seat they occupy at a given moment. From my limited experience in teaching in secondary schools, pupils are closely monitored and controlled. Classroom management is a valued skill and success – is pupils working quietly (and preferably learning). Even in the more relaxed atmosphere of the FE college student registration and monitoring is normal. Rooms are allocated for classes and attendance expected – sanctions for non or late attendance. These systems situate education in a particular place in space-time. The science laboratory is even more restrictive. Health and safety can restrict working patterns, procedures need to be followed closely. The uniform of lab coats and safety glasses need to be worn. I am thinking here of the typical educational laboratory for science at secondary and FE institutions; in particular, those used for students, like mine, studying an A level or similar syllabus. Field trips and other external studies may occur but, in my experience, these are few and far between.

The VL is restricted in a different way. Gone are the constrains of time and space. VL can be access at any time or in any place, although timetabled lessons in a computer room may be the best option, as Wörner, Kuhn and Scheiter (2022) found 'students with explicit instructions gained more conceptual understanding'. There is freedom to spend as much time as required repeating, revisiting, exploring. Supervision is not required - health and safety in the VL is not a physical issue. However, there are still restrictions. Probably the main one (suggested in the preliminary study (Peirson, 2020) although this needs further investigation) is the influence of external factors e.g.

- the type of access device (e.g. phone, tablet, laptop or VR),
- the physical space for access (e.g. bedroom, bus or computer room),
- distractions (noise, lighting, temperature, posture, comfort etc.),
- collaboration (working alone or with others, either physically or virtually).

These I feel are largely related to the concepts of aesthetics, discussed above. Also, there is a relation to the Gestalt principles, again discussed above. The factors identified by Peirson (2020) need to be part of the discussion with students of their experience in the VL and these contrasted to the much more controlled environment of the real laboratory; although this is beyond the research questions of the present study.

A second area of restriction for the VL is the nature of the laboratory. In Chapter 1, different types of VL were discussed ranging from simple illustrative animations, up to immersive VR. The choice of sophistication may be educational, or more likely at the present time, practical – based on availability. This can be related back to the concept of ontology – does the learner feel that the VL they are experiencing is 'real'? What does reality feel like for these students who may spend much of their time in a virtual world? Do they believe the results? How do they feel about a contradiction between what is seen in the VL and in the real laboratory? - this is closely related to the discussions in Chapter 2 about theory-laden observations.

A third strand is related to epistemology, to the extent that the VL allows the students to gain knowledge. What is it that the students are learning in the VL, is this different to the real laboratory? Sennett (2009, p. 125) talks of the 'craftsman, engaged in a continual dialogue with materials' something which is not possible in the disembodied VL and considers the 'complicated repertoire' (ibid, p. 50) of procedures which are developed by medical staff, leading to the 'embedding' of skills and ‘the hands-on transmission of knowledge from generation to generation’ (ibid, p. 57). Moreover, what is the knowledge which is transferred via the VL? Weisskopf (quoted in Sennett, 2009, p. 41) comments about his students - ‘When you show me the result, the computer understands the answer, but I don’t think you understand the answer’. I wish to know how students experience learning in the VL and if it is different to the real laboratory.

A fourth area for consideration is that of ethics: here I mean the ethics of the VL (the ethics of the study are discussed below). Any educational process has an ethical dimension, there is a power relationship between those who have knowledge and those who wish to gain it. Often this is enhanced by the knowledge holder also being the gatekeepers of achievement. For example, I as a teacher, mark and decide on the grades for BTEC and Access courses, and the 2021 A level as well. I also assess the pass/not completed grades for the A level practical assessments for A level chemistry (OCR, 2021). These assessments are internally and externally verified, but essentially, the power lies with the teacher and awarding body. So, what is judged as correct is a combination of teacher, verifier, college and awarding body. However, for the VL it is the manufacturer, or maybe the coder who decides, how the VL behaves and so how knowledge is transferred – indeed what knowledge is transferred. The power to decide on what is knowledge is now located externally. In a sense this is always the case, textbooks and other resources are also sources of knowledge. Students are taught to balance the competing ideas of different voices. This is particularly true in the humanities, in science there is as Kuhn suggests much more of an adherence to a paradigm.

Methods

My Perspective

As a practitioner-researcher I am situated within my study. I have tried to take account of this in balancing my views of the results, but inevitably there will be biases. I have tried to ameliorate this by presenting my reflective, thoughts as part of the thesis, to allow the reader to better judge the trustworthiness and validity of what I am saying.

Purpose of Research

There are several reasons for carrying out this research and these are briefly discussed, under broad headings.

Exploratory

I am curious and want to know about the world around me. I have an interest in science – Hanson’s philosopher’s (1962, p. 31) ‘hard’ facts or Russell’s (2000, p. 132) scientific facts; but also, how we see and learn about the world. The VL is a way of exploring the world, or perhaps a different world. Is the world based on some solid reality or is it an ever-changing response to our interaction (or transaction) with it or a construction present only in my mind? The VL gives perhaps two versions of the same thing – a digital twin. This gives the student the chance to think about reality and the trust we put in one version of it.

Descriptive

The research needs to describe, as well as possible, my version of the reality. To record in a way in which others can see what I have seen and feel what I have felt. To describe not only the facts but also a little of the experience. Research like this can never be reproduceable in the sense of the scientific method but might provide a 'sense of the whole … built from a rich data source' (Connolly and Clandinin, 1990).

Explanatory

The research might help to explain the relationship of the student to the reality which they are experiencing. Why do they feel as they do, working in a real or VL? What are they really learning? If the VL is the embodiment of theory and the real laboratory is focused on 'presuppositionless' observations (O'Hear, 1990, p. 16), how can these be reconciled? Can we explain what happens when these two views conflict?

Structure of this Research

This research does not set out to prove or disprove a hypothesis, its purpose is rather, exploratory. I want to find out about a field which, to me at least, is unclear. I want to understand how a student feels and learns when working in a VL and if this is different from being in a real laboratory. From this idea I have developed some rather tentative research goals.

Research Goals

So, I want to explore the extent to which students become aware of issues underlying the concept of the virtual *science* laboratory. How do they view science and in particular practical science? Do they accept the VL as a genuine version of reality? Do they feel that their experience in a VL provides a trustworthy experience? I will also tentatively explore if/how knowledge is generated differently in the real and virtual science laboratory and how students feel about their learning? This is all vague, I need to be more specific, so I begin to tighten my ideas, to make the task more manageable.

Research Aims

The aim of the research is then to gain some insight into what students think about their learning in the two environments. Although each student has an individual learning experience, I want to throw light on the themes which run through their experience. In particular, exploring how students relate their experiences of real and virtual laboratories. This is pursued though a largely interpretive perspective where knowledge is generated through inquiry into the views of participants. This is qualitative data, which is intended to illuminate the issues, rather than logically test any hypotheses.

Research Questions

In a limited study, such as this, there needs to be quite focused questions. These have been chosen as the starting point or framework for the study. Student responses will provide tentative answers to these questions. However, the responses are also likely to raise further questions and provide insight into questions which have not been thought of; I must remain alive to these possibilities when carrying out the research.

The questions which form the basis of the research are:

- RQ1: The extent to which students experience learning in a VL as a mirror of reality?
- RQ2: The extent to which students regard the results of experiments conducted in these environments as trustworthy?
- RQ3: The extent to which teachers can have confidence in the educational value of learning in the VL?

(Note: RQ2 has been extended to cover both types of laboratory, originally, I was only thinking of the trustworthiness of the VL).

Ethical Considerations

As discussed above there are three main ethical themes, concerning: rules and duties, consequences and moral values (Hursthouse and Pettigrove, 2022). These have been used to frame the following descriptions of the ethical considerations made when conducting this project.

Rules and duties

The study was carried out in line with the BERA (2018) guidelines, current at the time of the work. All participants gave informed consent (BERA, 2018, 8) and were informed of their right to withdraw (BERA, 2018, 31). Each participant was given copies of the consent and information documents (Appendix 3), which they read and signed; additionally, the procedures and safeguards were explained verbally to each class. Students needed to "opt in" by completing the optional survey and volunteering for the interviews; some students did not complete the survey. Prior to each interview participants were reminded of their right to withdraw at any point. Care has been taken that no harm or disadvantage results from the participation in this study (BERA, 2018, 34-36), with any disclosure treated in accordance with the safeguarding policies of the college in which this research took place.

Data has been collected and stored in accordance with BERA guidelines publication (BERA, 2018, 48-50) and the GDPR (2018) regulations. The where the results of the study disseminated by publication (BERA, 2018, 72) care has been taken to anonymise the identity of the participants (BERA, 2018, 40). Interviewees names have been replaced by letters and identifying references to the studied institution removed. The data reported characterising students and staff has been minimised to avoid possible identification.

The research was approved by the University of Sunderland Ethics Committee (see Appendix 4); and by a relevant member of the Senior Leadership Team for of the college where this research took place (see Appendix 5). Although this research has been part funded by the Education and Training Foundation (ETF), the Foundation did not influence the conduct of the research or its outcomes. The study was therefore framed within the necessary structure for compliance, meeting the ethical requirement for rules and duty. However, there also needs to be consideration of the other aspects of ethics.

Consequences

Husband (2020a) suggests that ethical considerations go beyond mere compliance with regulatory requirements. This raises some questions regarding the consequences of this study for participants. Husband (2018, 2020a, 2020b) carried out interviews with experienced teachers about their initial teacher training, Subsequently, some of those interviewed contacted Husband to report that the interviews had 'been the catalyst that prompted deeper thinking and reflection' (Husband 2020a). The article shows evidence to support the view that 'interview situations can lead to a greater level of engagement and reflection than anticipated' (ibid). Husband (2020a) is concerned that the participants consent cannot be truly informed unless 'it could be made clear that in answering questions and engaging in discussion, respondents may consider issues that they had not previously considered that could potentially change their perspective or views on an issue or area of exploration' (ibid). In the light of this work the current study needs two be considered in two parts: interviews with students and interviews with teachers.

This is a practitioner research study and therefore fundamentally different to the external research described by Husband (2018, 2020a, 2020b). In that work there is no indication that the interviewees were known to the interviewer. Both students and teachers were personally known to me and therefore had separate relationships outside the interview. This is an integral feature of practitioner research, which I would argue affects the nature of the term 'informed consent' (BERA, 2018 8 and see Kirby (2020) for a discussion of children's informed consent). The nature of the relationship between people who know and presumably trust each other (or they would not have engaged in the exercise) is very different to that with an external researcher. The difference will depend on a range of factors (beyond the scope of this work) but is unlikely to be straight forward. This is even more so as Husband (2020a) argues 'that in answering questions and engaging in discussion, respondents may consider issues that they had not previously considered that could potentially change their perspective or views on an issue or area of exploration' (which will be shown below is the case with this study).

Next, I will consider the effect on each group in relation to consent, firstly the teachers, as they are closest to the case described by Husband (2020a). The question Husband poses is does their consent extend to the possibility that by 'participating in the research, the researcher and interviewee are engaged in investigation and the sharing of ideas through discussion … [they are] actively constructing knowledge in partnership'? I am not sure that both the teachers interviewed were alive to this possibility, however, they were aware of my interest in the subject of VL. Also, I feel they believed I wanted to persuade them as to the value of VL. Although, these were explicitly research interviews, without the formal recording of the interview, they could easily have been considered to be "professional discussions" between colleagues. Those entering into such discussion might then reasonably expect there is a 'process of reflection and in so doing the act of answering the questions and entering discussion becomes part of the process of critique and learning in practice which in turn, could lead to change' (ibid).

Considering now the students, here I feel the issues are different. Husband (2020a) states his 'research had been designed to understand the experiences of the respondents and not shape them'; and this indeed was the aim of the research here. However, the students were interviewed by me, their teacher within the college during the normal working day. Under such circumstances I would argue that they would be expecting to learn. The activity of 'actively constructing knowledge in partnership … that may require them to consider issues in a depth not explicitly previously engaged in', is, I would suggest, part of the learning experience that any FE student might expect. I would therefore argue that there is already tacit consent to the process that may illicit 'deeper thinking and reflection' (ibid).

There are also several issues regarding 'informed consent', which although beyond the scope of this thesis are briefly outlined here. These relate to such concerns such as, whether 'informed consent' can ever really be possible, particularly in the case of practitioner research where there are many implicit and explicit power relationships in play. There may also be an element of trust in these relationships which would alter participants view of any potential risks. A further issue is whether under 18s who are "expected" to be in education are there of their own volition? and so, do they give 'informed consent' to the education process in a wider sense. More particularly in this study, how do they view a request from their teacher to participate in the interview process, some students may interpret this as some sort of requirement, notwithstanding the information presented to the contrary. Additionally, would interviewees have the confidence to withdraw consent once the interview process had begun?

In summary, when carrying out this practitioner research study several ethical issues have been addressed. The formal rules set out by the University and BERA (2018) requirements have been followed. Moreover, the consequences of the research for participants have been accessed and although

they may have been exposed to ideas outside their "comfort zone", this is not beyond what could be reasonably be expected in the educational setting where they work or study. The issue of informed consent particularly for those under 18, is beyond the scope of this work.

Choice of Research Methods

The aim of this research is to capture something of the experience of students of learning in real and virtual laboratories. A number of studies reported in Chapter 2 focused on quantitative data. Quantitative data has the advantage of being easily processed and for me as a scientist – familiarity. However, it is not well suited to give a valid and believable description of the 'experience' of students. It is unlikely that a spreadsheet or graph can provide a complete description of experience. As Sellberg, Nazari and Solberg (2024) says 'the everyday educational practices at work in virtual labs are largely black-boxed in STEM higher education' (and probably not considered at all in FE). Qualitative data would seem much more suited to the task: experience is more likely to lead to words, gestures, movement and feelings. Most qualitative data is captured as words, predominately the written word (Denscombe, 2017, p. 305). The data in this study is also mainly recorded in the form of the written word, some of which has been transcribed from speech. Denscombe (2017) offers five qualitative data analysis methods suited to the analysis of 'talk and text' (ibid., p. 311). These are described briefly here before setting out the reasons for the choice of thematic analysis, discussed in the next section.

Content analysis is concerned with the importance of words within the analysed piece. It is the type and frequency of words used which allows for a clear and quantifiable analysis. The method can provide a measure of the importance of particular words or phrases within the data. Coding allows for the building of a map of relationships and between them. The focus is on content rather than context, resulting in a 'quite positivistic … approach' (Denscombe, 2017, p. 312). Although the method provides a clear and repeatable way of quantifying data, much of the inherent subtilty and context of qualitative data is striped out by the process. Denscombe (ibid, p. 314) concludes that 'content analysis is at is best when dealing with aspects of communication which tend to be more straightforward, obvious and simple'.

Grounded theory has been developed to aid interpretation of text within developing theories (ibid, p. 314). Here analytic coding is used – related to categorising the data. This is developed into a hierarchy which can reveal new concepts. The process is started by a deep engagement and familiarity with the data. This leads to insights and ideas which are recorded in memos. The data is then coded, with codes applied to a variety of entities, such as field note, documents, photographs as well as interview transcripts. The codes are then grouped or categorised to 'make the link' (ibid, p. 315). The next step is to merge categories where there is an overlap of common features, in this way some parts of the data emerge as more important. Once this stage is complete then the next task is to build a hierarchy of higher-level categories which cover the lower-level codes. At this stage it is important to revisit the data to ensure that the analysis is a fair representation of the data. This leads to the generation of a 'data analysis spiral' (ibid, p. 316) allowing the identification of key concepts. Then the development of concepts from this collection of codes, which reflect the underlying data.

Discourse analysis seeks to identify the underlying factors which shape text. The aim is to bring out the '*implied meaning* of the text'; (ibid, p. 317) including cultural assumptions, ideology, political and historical factors, which underlie the material. Essentially, the method seeks to extend the data to give a view of the wider picture. The way this extended panorama is developed can depend critically on the researcher and their view of how the data analysed fits into a wider context. Inevitably, this process is subjective and so is not amenable to an audit trail or other verification. I do not intend to use this method as it relies on the insights of an experienced and knowledgeable researcher, well versed in qualitative analysis – so I am unlikely to achieve a useful interpretation.

A similar method is that of conversation analysis which focuses on 'how things get done through language use' (ibid, p. 319). This tends to focus on everyday talk, so is not suited to the more technical discussions examined in this work. For story-based text, narrative analysis, provides a method of analysis (ibid, p. 320), however, my data is not suitable to analysed in this way.

Although the main data is text based, VL provide a rich source of images, which are amenable to analysis. Denscombe describes two main reasons for image analysis (ibid, p. 321): for factual information; or for cultural significance and symbolic meaning. These can be related to three elements of analysis: the image; the producer; and the viewer. A brief attempt at such an analysis is presented in Appendix 19.

Thematic analysis

The technique of thematic analysis has been selected for this study as it has a well-established methodology and has been used in a number of studies (see Nowell et al., 2017, and references there in). The basis of the method is to identify themes within qualitative data. The process is similar to other methods discussed above, requiring a familiarity with the data, to allow researchers to make judgements about coding data. Nowell et al. (2017, p. 3) cite trustworthiness as a way to demonstrate that their 'research findings are worthy of attention' (this is discussed in the next section). The basis and process of thematic analysis are discussed in more detail in Chapter 4, where it is applied to the data from this study.

Trustworthiness

A key feature of the method is the focus on 'trustworthiness' through an emphasis on the criteria developed by Lincoln and Guba (1985, pp. 299-327): these are credibility, transferability, dependability and confirmability; corresponding to the more 'conventional terms' of internal validity, external validity, reliability and objectivity. Lincoln and Guba (1985, p. 301) suggest that to ensure credibility there are five requirements:

1. 'Activities increasing the probability that credible findings will be produced'. These activities are identified as:

    - Prolonged Engagement; this can be assured in this study, as I have known and taught the students for at least 8 months (phase 1) or 14 months (phase 2) for around 5 hours per week. I have worked with the members of staff surveyed (phase 3) for a number of years, some for over 8 years and the staff interviewees (phase 4) one for 9 months and the other over 3 years.
    - Persistent Observation; this is ensured at least in part, in that all the real laboratory practical activities were observed by me as part of the course practical assessment, activities in the VL were often in class where I was able to observe students. The interviews are carried out personally.
    - Triangulation (ibid, p. 305); this occurs to some extent, in that, phases 1 and 3 use mixed methods and phases 2 and 4, a different purely qualitative method. Data is also gathered from students, in more than one group, and teachers in different areas of science. However, the nature of the study inevitably means that triangulation is less than for some other methodologies.
2. 'Peer debriefing'. This is an intrinsic part of the Ph.D. programme, in that the study needs to be explained to my supervisor and the examiners.
3. 'Negative case analysis'. This is the 'process of revising the hypotheses with hindsight' (ibid, p. 309). No initial hypotheses were adopted because this research is inductive in nature, so the process 'to refine a hypothesis until it accounts for all known cases without exception' (ibid, p. 309), is a natural process when working with the data.
4. Referential adequacy. This refers to the quality of the raw data which can be provided to back up the veracity of any findings or conclusions. For phases 1 and 3 of this study the original Google Forms are available and for phases 2 and 4 the original interview recordings are available (however, participants would need to consent before these were released to a third party).
5. Member-checking. As the data in phase 1 has been provided anonymously – this can only be the broad conclusions can be fed back; while for the other phases, data and conclusions can be checked with participants. The interview material was sent to each of the participants to allow them to check its accuracy.

According to Lincoln and Guba (1985, p. 316) transferability for a naturalistic study 'can only set out working hypotheses together with a description of the time and context in which they were found to hold'. In this work the time and context are described throughout the thesis, but mainly in this and the next chapters. The working hypothesis in line with the negative case analysis argument will only be developed in Chapter 5. The authors go on to say, 'the naturalist cannot specify the external validity of an inquiry; he or she can provide only the thick description necessary to enable someone interested in making a transfer to reach a conclusion about whether transfer can be contemplated as a possibility'. To this end, descriptions of the students and the college are provided in as much detail as possible, whilst maintaining anonymity. This conforms to Lincoln and Guba statement that ‘what constitutes ‘proper’ thick description is … still not completely resolved’ (ibid, p. 316). While Nowell et al (2017, p. 3) note that for ‘qualitative research, [transferability] concerns only to case-to-case transfer’, so my descriptions need to be rich in context for others to use them.

For the dependability requirement Lincoln and Guba (1985) rely on the earlier work by Guba, who has set out four criteria. These are:

1. That because there can be ‘no credibility without dependability’ (ibid, p. 316), establishing credibility ensures dependability; however, they admit this is a weak argument. I have set out above how I hope to ensure credibility, thus also suggesting dependability.
2. The ‘overlap method’ is equivalent to the triangulation described for credibility, above. It has not been possible to carryout extensive triangulation in this limited study, but correlation between phases 1 with 2; and 3 with 4, might provide some reassurance.
3. Guba proposes a process of ‘step-wise replication’; as this requires at least two teams of enquirers, it is not possible for a lone researcher, such as myself to use this method.
4. This is the process of an ‘audit’ of the study, similar to a financial audit. The audit examines the *process* of the enquiry and the *data* produced. In this study the audit is provided by my supervisor during the planning, collection and analysis; then by my supervisor and examiners at the end of the Ph.D. process. This audit process is the best guarantee of dependability for this study according to the criteria set out by Lincoln and Guba (1985).

The authors go on to say that the confirmability of the enquiry is also supported by the audit process described above. They set out in some detail an audit process which was developed by Halpern (given in some detail in ibid, pp. 320-327 and Appendices A and B). This is a detailed process which is beyond the limited scope of this study.

The development of trustworthiness set out here is essentially based on inductive logic. This process, particularly in the context of qualitative results does not always follow a straight path. Bassey (Hammersley, 2001, p. 219) talks of ‘fuzzy’ generalisations, differing from ‘conventional logic in treating membership of categories as a matter of degree, so that there are not fixed boundaries between categories but, rather, gradients falling away from relatively standard cases to more marginal ones, these possibly lying on the borderlines of several categories. The consequence of this is that truth itself becomes a matter of degree. Although, criticised by Hammersley (ibid) as not really distinct from the logic of experiment, showing ‘what *could* happen’ (ibid, p. 223). Hammersley (ibid. p. 222) also notes that the results are presented as ‘fuzzy predictions designed for use and accompanied by best estimates of trustworthiness’. This he finds worrying as it ‘circumvents the role of the research community in validating findings’ (ibid, p. 222). Similarly, Wittgenstein (in Kuhn, 1996, pp. 44,45) developing the concept of ‘natural families’ requires these to be connected by a ‘network of overlapping crisscross resemblances’ (ibid, p. 45). Kuhn points out that without commonly understood natural families – so, they are ‘overlapped and merged gradually into one another’, then there needs to be ‘a set of common characteristics corresponding to each class’. This sets a more ridged framework again, for Kuhn, truth is within the context of a paradigm, if you accept the paradigm then certain things are ‘true’; this may not be the case within a different paradigm (also see the discussion of the FRA in Chapter 2). However, the concept of fuzzy generalisations is ‘useful in suggesting that we can have theoretical knowledge of causal relationships before we can produce precisely and fully formulated scientific laws—indeed, perhaps even when such precision and completeness are unattainable’ (Hammersley, 2001, p. 223). This is the situation for a limited study such as the one recorded here.

It is worth noting that Sellberg, Nazari and Solberg (2024) employ a technique similar to thematic analysis – *narrative synthesis* when reviewing VL research papers. This, they claim, provides a 'coherent and logical account based on the principle of juxtaposition of different studies' (ibid). While, this might prove a useful extension to the thematic analysis used here, it is beyond the scope of this work.

Mixed methods

While there are different perspectives on the nature of knowledge each of which favours their own type of data collection and analysis, there is also merit in considering mixed methods, that is a combination to techniques from different perspectives. Onwuegbuzie and Leech (2005, p. 375) claim that 'Mono-method research is the biggest threat to the advancement of the social sciences' and maintaining that 'the epistemology does not dictate which specific data collection and data analytical methods should be used by researchers' (ibid, p. 376). The authors go on to note 'the inclusion of qualitative data can help explain relationships discovered by quantitative data' (ibid, p. 383), this is an important feature, allowing us to use our research to inform future actions. While Clarke and Visser (2019, p. 457) claim the value of using a mixture of qualitative methods 'can ameliorate some of the tensions and limitations inherent within the pure methodologies'. This gives a richer, fuller, description of the research. This research uses both survey and interview data in an attempt to provide a wider picture.

Choice of VL

When choosing the VL, and indeed the real practicals, for this study, the options are severely constrained by the context, curriculum and availability. In the context of practitioner research in the FE sector, there is little or no money to purchase nor time to develop software. Also, there is limited training opportunities with students to use much beyond the basic freely available VL programs. The restrictions of the curriculum mean, for the A level chemistry classes I teach, that I need to use material which is directly relevant to their course. Moreover, the software needs to be of an appropriate level educationally, to work on relatively unsophisticated machines and to be free. The students have therefore largely been exposed to simulations from the PhET (2024) suite of programs and the VL screen experiments provided by the RSC (2024). One of the main VL experiences, for the students in this study, has been the set of four RSC titration screen experiments. These correspond well with the OCR (2015) PAG activities with the mapping shown in Table 18.

Table 18 showing a comparison of the RSC (2024) screen experiment activities to those undertaken in the OCR PAGs.

RSC	Description	PAG	Description
Titration 1	making up standard solutions, acid base titration	2.1	making up standard solutions, acid base titration
Titration 2	concentration of ammonia – weak base titration	11.2	ammonia – weak base titration
Titration 3	concentration of aspirin – weak acid titration	11.2	ethanoic acid – weak acid titration
Titration 4	analysis of iron tablets – redox titration	12.1	analysis of iron tablets – redox titration

The RSC (2024) experiments have been developed to provide an engaging background narrative to the titration experiments. Each is set in its own scenario in which the titration plays a pivotal role. For example, Titration 1 is based around a supposed acid spill into a river and the need to neutralise the acid before it harms a site of special scientific interest. Students are led from screen to screen, then work in a VL to make up a standard solution and then use this in an acid-base titration. The practical chemistry involved in this process is almost identical to that carried out in the laboratory in the PAG 2.1 experiment. Both making up standard solutions and, in particular, learning to perform titration experiments, could be considered to be one of Shulman's (2005) 'signature pedagogies', for learning chemistry. The process has also been gamified (see for example, Tauber, Levonis and Schweiker, 2022), in that, points are awarded for correct answers and procedure.

Conducting the Research

The research was carried out in two main parts, relating to students (Phases, 1 and 2) and staff (Phases, 3 and 4). Each part was intended to be conducted in two sections; the first or scoping phase focused on the participants' overall impressions of real and virtual laboratories. The second phase probed deeper with the intention of providing answers to the research questions posed above.

Phase 1

This phase used an online questionnaire to investigate students' responses to questions based on Holman's (2017) five outcomes (Table 2). The questionnaire had two questions about each outcome, the first, on a five-point Likert Scale (see Sue and Ritter, 2012); the second, a more open question, inviting a text answer; an example is shown in Appendix 6. Both types of questions address the comparison of experiments carried out in real laboratory with those in VL, the results are recorded in Chapter 4.

The questionnaire was given to four groups of students, two first year and two second year, studying the OCR 'A' Level Chemistry A syllabus (OCR, 2021). They are members of the 6^{th} Form, which is part of a larger general FE college. All students are taking at least 2 other A levels, with a few also taking a fourth. There is a minimum requirement for students to have English GCSE grade 4, with Maths and Chemistry (or Combined Science) at 6 or above. Most of the students have come to the College straight from school and are 16-18 years old. The cohort also contained a few older students up to the age of 28. For several of the students English was not their first language, while others live in multilingual households.

The surveys were undertaken in February/March and May 2022, towards the end of the academic year. Both first and second years had experienced a number of virtual simulations and VLs; as well as, a large range of practical activities based on the OCR (2015) PAG experiments. The questions are set on a Google Form (see Appendix 6), accessed from a link in each group's Goggle Classroom. There were a total of 34 responses recorded; these results are discussed in Chapter 4.

Phase 2

For this part of the study a number of questions were prepared based the research questions given above. The questions were designed to match the themes in these questions and invite conversations which lead to towards a greater understanding of the students' views. An example of the question script is given in Appendix 7. The questions are intended as a framework to shape the conversation rather than be a strict question and answer sheet. Being a research practitioner, and until one month before the first interview, the class teacher, meant that the interviews were less formal and more conversational than if I were an external researcher. I have known these students for around 18 months; hopefully, this led to more open responses.

Students who had expressed an interest in contributing were contacted by email; initially only four were available at a mutually convenient time. The first four interviews were conducted on one afternoon in late January 2023. A further student was interviewed at the end of March 2023 and the final pair at the end of April 2023. (It would have probably been better to interview all students over a shorter period, but this was not practical.) The students in this part of the research had already contributed to Phase 1. For simplicity and to retain anonymity, the students will be identified alphabetically in the order the were interviewed, their details are given in Table 19.

Table 19 giving details of the students interviewed in Phase 2 of the study

Student	Gender	Native English speaker	Chemistry A level grade	Other A levels	Confirmed transcript
A	F	Y	E	Maths, Physics	Y
B	F	Y	D	Biology, Maths	N/R
C	F	N	U	Computer Science, Physics	Y
D	M	N	E	Biology, Maths	Y
E	M	N	A	Biology, Psychology	N/R
F	F	Y	U	Criminology (Diploma), Psychology	Y
G	F	Y	B	Biology, Psychology	Y

The first interview was with two students (A and B) who had decided they would like to talk with me together; they also often work together, in class. Students C and D were interviewed separately from each other. The interviews were conducted in a small room within the College. Student E was interviewed in a classroom. Students F and G (who were in different groups for chemistry) were interviewed together in a small College room.

The interviews were recorded, to allow transcription, as I am not capable of making adequate written notes. The recordings were made using the Google Meet software on two laptop computers placed on the desk between myself and the students. The files were stored in an MP4 format. The original files were stored on a Google drive and copies transferred to a laptop for analysis. In both cases access to the files is controlled through password protection. The Google Meet software provides a basic transcription; however, this is not completely accurate. So, I have used the Descript software (Descript, 2023) to transcribe the interviews, this appears to be slightly more accurate. The main advantage of this tool is that it provides a simultaneous audio and video display with the transcription so that it is relatively easy to go word by word through the transcription whilst hearing the synchronised audio, so I was able to check and correct the transcription. Although most of the audio was clear there were some occasions where the words and/or speaker are not clear. I therefore compared the second recording to clarify the point. I am therefore fairly confident that the transcript fairly reflects the words spoken, if there is any uncertainty then the choice of words is based on my understanding of the context and knowledge of the interviewee. The first interviews (A-D) were recorded without video, as it seemed less intimidating, however, it turns out to be easier to distinguish, speakers and context when a video recording is also available; so, for all the subsequent interviews video was recorded as well. Extracts from the corrected file transcriptions are given in Appendices 8 – 13, while the analysis is discussed in Chapter 4.

Each participant was given a copy of the edited transcripts, students A, C, D, F and G confirmed that these were a fair reflection of their views: there were no responses from students B or E. This, in part, meets Lincoln and Guba (1985, p. 301) credibility requirement (5) for member checking.

Phase 3

A Google Form survey similar to that used for students was sent by individual email to 10 science staff working within the Colleges Science and Sixth Form areas. An example of the questions is shown in Appendix 6. The form was initially sent in late April 2023, resulting in only one response. After subsequent requests, a total of 8 responses were recorded by the beginning of July 2023. The analysis is presented in Chapter 4.

Phase 4

A similar process was carried with interviews for science staff, as used for students, the questions were modified and are shown in Appendix 7. Two members of staff were interviewed; this low number is due to the limited number of science staff and that of those, most felt they did not have sufficient knowledge or experience to comment; moreover, staff had limited time available. The first interview was carried out in late June 2023. The second interview (early July 2023) was carried out on the last afternoon of term, after the staff celebration event. This may have led to the interviewee giving a more open and candid interview, as they had consumed a bottle of beer with their lunch. The interviews were recorded in classrooms on just one computer, but essentially using the same method as described for the student interviews, in Phase 2. Extracts from the transcriptions are given in Appendices 15-18, while the analysis is again discussed in Chapter 4.

Both teachers S and T were given a copy of the edited transcript of their interview, and both confirmed that these were a fair reflection of their views. This goes further to meet Lincoln and Guba (1985, p. 301) credibility requirement (5) for member checking.

Summary

This is a brief summary of the chapter, before moving on to look at the findings of the study. In Part 1, I briefly explore the three main areas of Greek philosophy: Ontology, Epistemology and Value Judgments (Ethics, Aesthetics). Ontology is considered in terms of the two main traditions: positivism and interpretivism. Positivists hold that reality is 'reductionist and deterministic' (Waring, 2012 p. 18); it is subject to time and context free laws of cause and effect. Alternatively, interpretivists suggest that an individual reality is constructed by the mind. The interpretivists rely on the interpretation of reality, informed by the theories and experiences of the observer. This view of reality is personal to the observer.

Epistemology is 'concerned with what the criteria are that allow distinctions between 'knowledge' and 'non-knowledge 'to be made' (Usher, 1996, p. 11). There are traditions following on from the two ontological perspectives: realist and interpretive. The realists or positivists 'discover' facts which are the basis of knowledge. They use the methods of experimental science with the independent investigator making 'presuppositionless' observations (O'Hear, 1990, p. 16), in a controlled environment. Knowledge is developed though hypothesis and theory, grounded in the results of empirical experimentation and observation. Alternatively, interpretative approaches do not 'see direct knowledge as possible; it is the accounts and observations of the world that provide indirect indications of phenomena' (Waring, 2012, p. 16). This suggests that all knowledge is mediated through the observer.

I have explored how knowledge is developed through theory, and how the choice of theory can affect the knowledge that is gained – this is particularly relevant to VL. Knowledge can be obtained by deriving facts from observations. This process depends on the logical interpretation of these observation through theories. There are different ways to determine the value or truth of a theory, these are discussed and compared. The methods of deduction, induction, explanation, hypothetical-deductive, inference to the best explanation, inquiry, Bayes, Gestalt are considered as well as the perspectives of realism, positivism and instrumentalism. There then follows a description how knowledge can be obtained through the recognition of patterns and how this relates to Blooms' taxonomy and VL. The ideas of Ethics, Aesthetics, sophistication and control are briefly reviewed.

In Part 2, the positivist and interpretive perspectives are related to methodologies which describe how things should be processed during the research. Waring (2012, p. 16) says that 'methodology asks 'what procedures or logic should be followed?''. This gives a steer to what might be expected as a focus for investigation during research. Positivists would favour the deductive logic, working from general laws to investigate particular cases. This is the driver for Popper's theory of 'falsification' discussed in Chapter 2. However, there is little 'real world' evidence that deductive logic can be applied to non-trivial problems. As O'Hear (1990, p.27) puts it 'the conclusion cannot go significantly beyond the premisses' – a deductive process can tell you little more than you already knew.

The interpretative approach relies on inductive logic, which Hume, Goodman and Popper have suggested is unreliable. However, it provides a framework for the description of the qualitative interactions which occur in the education environment. It is through these interactions that a greater understanding of the situation can be gained.

As a practitioner-researcher I am situated within my study. I have tried to take account for this in balancing my views of the results, but inevitably there will be biases. I have tried to ameliorate this by presenting my reflective, thoughts as part of the thesis, to allow the reader to better judge the trustworthiness and validity of what I am saying.

Table 20 showing the research questions

RQ1	The extent to which students experience learning in a VL as a mirror of reality?
RQ2	The extent to which students regard the results of experiments conducted in these environments as trustworthy?
RQ3	The extent to which teachers can have confidence in the educational value of learning in the VL?

The aim of the research – to understand students experiences of real and virtual practical science; is proposed and three specific questions are proposed, these are shown in Table 20. The ethical considerations for the study are then set out. This is followed by a description of the practical aspects of the study. There is a discussion of the research paradigm, I am using interactionist approach, with the data largely gathered from interviews. The reasons for focusing on a thematic analysis of the interview data is then discussed. A brief discussion is given of the reason for the choice of the RSC screen experiments as the main example of VL in this study. Finally, some of the details of the data collection methods are recorded, which are summarised in Table 21.

Table 21 showing a summary of the data collection methods

	Phase 1	Phase 2	Phase 3	Phase 4
Method	Survey	Interview	Survey	Interview
Participants	34 students	7 students	8 teachers	2 teachers
Example Questions	Appendix 6	Appendix 7	Appendix 6	Appendix 7
Analysis	Likert / Thematic Analysis (text)	Thematic Analysis	Likert / Thematic Analysis (text)	Thematic Analysis

CHAPTER 4

DATA ANALYSIS AND EMERGING THEMES

Every inquiry is a seeking. Every seeking gets guided beforehand by what is sought.

(Heidegger, in Hanson, 1962, p. 24)

Introduction

Data are created from observations and observations are made in a context. As we saw in Chapter 2, observations are theory-laden and so will depend on the observer. In Chapter 3 some of the underlying views and assumptions which I bring to this work were examined. In this Chapter the data is presented and some of the themes which emerge are identified. Where the data is presented, I have indicated written material in roman type contained within single quotation marks. Where spoken responses are transcribed, these are indicated by *italic* text. The interaction of identified themes with the frameworks from the literature, which emerged in Chapter 2, are then discussed in Chapter 5.

The structure of this chapter is framed using the paper by Nowell et al. (2017) as a guide. The focus of this paper is the aim 'to Meet the Trustworthiness Criteria', which needs to be conducted 'in a rigorous and methodical manner to yield meaningful and useful results' (ibid). In particular, the focus is on thematic analysis which is claimed to be 'a relevant qualitative research method' which is capable of generating 'knowledge grounded in human experience' (ibid). Nowell et al. (2017) suggest that thematic analysis can be used when working with large data sets. While this data set is relatively small, it might be hoped that this process will still provide useful insights.

Thematic Analysis

Thematic analysis is an approach which provides a model for interpreting qualitative data. The concept is to identify those themes or strands which flow through the data. These are brought out by the use of coding. The process is first to understand the data in such a way as to be able to choose words or phrases which 'simplify and focus on specific characteristics of the data' (ibid). These codes provide 'explicit boundaries' and can be used at several levels. Hierarchical coding allows the generation of an overview whilst allowing for detail to be retained. Coding is not intended to be a static process, but to develop with 'thoughts and ideas …evolving' as researchers engage 'more deeply with the data' (ibid).

The next stage is to identify themes. Following, Nowell et al. (2017) I am using the definition provided by DeSantis and Ugarriza (quoted in ibid) – 'A theme is an abstract entity that brings meaning and identity to a recurrent experience and its variant manifestations. As such, a theme captures and unifies the nature or basis of the experience into a meaningful whole'. The search for themes can be either inductively or deductively driven.

There is now a stage which compares the developed themes against the original data. It is important to identify 'whether the themes accurately reflect the meanings evident in the data set as a whole' (ibid). Some themes may to be combined as they have little supporting evidence, whilst missed connections may become apparent. The need for recoding is 'expected as coding is an ongoing organic process' (ibid).

Table 22 showing Nowell et al's (2017) study phases as a means of establishing trustworthiness during each phase of thematic analysis.

Phase 1: Familiarizing yourself with your data	Prolong engagement with data Triangulate different data collection modes Document theoretical and reflective thoughts Document thoughts about potential codes/themes Store raw data in well-organized archives Keep records of all data field notes, transcripts, and reflexive journals
Phase 2: Generating initial codes	Peer debriefing Researcher triangulation Reflexive journaling Use of a coding framework Audit trail of code generation Documentation of all team meeting and peer debriefings
Phase 3: Searching for themes	Researcher triangulation Diagramming to make sense of theme connections Keep detailed notes about development and hierarchies of concepts and themes
Phase 4: Reviewing themes	Researcher triangulation Themes and subthemes vetted by team members Test for referential adequacy by returning to raw data
Phase 5: Defining and naming themes	Researcher triangulation Peer debriefing Team consensus on themes Documentation of team meetings regarding themes Documentation of theme naming
Phase 6: Producing the report	Member checking Peer debriefing Describing process of coding and analysis in sufficient details Thick descriptions of context Description of the audit trail Report on reasons for theoretical, methodological, and analytical choices throughout the entire study

(reproduced from Nowell et al., 2017)

The next stage is to analyse the themes identified, defining and naming them. In this way they are given some character – 'identifying the story that each theme tells' (ibid). The data is now revisited in light of these themes to determine if they give a true reflection of the underlaying data. Nowell et al. (2017), following the work of King, suggest that 'themes should not be considered final until all of the data have been read through and the coding scrutinized at least twice'.

The final phase is reporting the findings. Here checking the trustworthiness of the analysis is key to the value of the work. It is essential that the reader is persuaded that the 'research findings are worthy of their attention' (ibid, p. 3). These stages are summarised in Table 22, taken from Nowell et al. (2017) who provide a step-by-step approach for the analysis.

Trustworthiness

In Chapter 3, the concept of trustworthiness in relation to this study was considered. Here the ideas are summarised with a focus on the practical application to the data collected in this study. Lincoln and Guba (1985, p. 287) caution that 'the study is for naught if its trustworthiness is questionable'. They suggest that conventionally researchers will ask themselves four questions to establish trustworthiness – these concern: truth value, applicability, consistency and neutrality (ibid, p. 290). Lincoln and Guba, identify these within the 'conventional paradigm' with internal validity, external validity, reliability and objectivity (ibid, p. 290).

The concept of internal validity is related to causality, which we saw in Chapter 2, may be difficult to justify even in the natural sciences. The work of Campbell and Stanley identifies eight threats to internal validity:- history, maturation, testing, instrumentation, statistical regression, differential selection, experimental mortality and maturation interaction (ibid, p. 291). Again, external validity relies on the concept of causality. It is defined in terms of the inference 'that the presumed causal relationship can be generalised to and across alternate measures of the cause and effect and across different types of persons, settings and times' (ibid, p. 291).

Rejecting the conventional paradigm in favour of a 'naturalistic paradigm' (ibid, p. 301); Lincoln and Guba set out an alternative set of 'trustworthiness criteria'. They assert, following Morgan, 'that different paradigms make different knowledge claims, with the result that what counts as significant knowledge vary from paradigm to paradigm' (ibid, p. 301). This reminiscent of the work of Kuhn, discussed in Chapter 2, where revolutionary scientific paradigms are held to be 'incommensurable' (Kuhn, 1996). They propose four criteria:- credibility, transferability, dependability and confirmability, as the basis for establishing trustworthiness, within the naturalistic paradigm. Nowell et al. (2017) give useful brief descriptions of these criteria, which are summarised in Table 23.

Table 23 showing the criteria for establishing trustworthiness, summarised from Nowell et al. (2017)

Criterium	Description	Enhanced by
Credibility	'the 'fit' between respondents' views and the researcher's representation of them'	prolonged engagement, persistent observation, triangulation, member checking
Transferability	generalisation of the enquiry, 'case-to-case transfers'	thick descriptions allowing other researchers to judge transferability
Dependability	a research process which is 'logical, traceable, and clearly documented'	readers are able to examine the research process, including an audit trail
Confirmability	'interpretations and findings are clearly derived from the data'	'credibility, transferability, and dependability' all being achieved; the use of an audit trail

Overall plan for the study

This study has been conducted in 4 stages which were set out in Chapter 3, for convenience they are summarised here:

Phase 1: online student survey generating quantitative Likert data and qualitative short text data.

Phase 2: face-to-face student interviews generating in-depth qualitative data.

Phase 3: online teacher survey generating quantitative Likert data and qualitative short text data.

Phase 4: face-to-face teacher interviews generating in-depth qualitative data.

Details of each stage are given in the following sections.

The preliminary study

The initial stage of the study (Phase 1, see below) produced preliminary data which designed to inform more the detailed studies, which follow. Analysis of the textual data from the survey uses the method proposed by Nowell et al. (2017). This has several advantages:

1. As a novice researcher in qualitative methods, un-familiar with thematic analysis, I need to train myself and trial the method.
2. I need to establish that the method of thematic analysis is likely to provide useful and trustworthy results for the main study I am undertaking.
3. I need to gauge the quantity and quality of data required.
4. I want to establish some initial themes which will inform the rest of the study.
5. I want to explore different possible methods of data collection.

The preliminary study is designed to give data which will start to answer the research questions set out in Chapter 3 and address the points above. To gather this initial data, I decided to use the same survey method that I had used previously, in the study for the University of Sunderland MA short course, some of which has been published (Peirson, 2020). In that study the questions were derived from a list given by Holman (2017) shown in Table 2.

Phase 1 data

Introduction

Data were collected as described in Chapter 3, using an online survey of students. The questions asked are set out in the next section, based on the benefits of practical science identified in Table 2. Some initial questions about accessing the VL and interest in science were included prior to these questions, to guide students to think about their experience of VL. The responses to these preliminary questions have not been analysed here, as they do not relate to the current research questions. There is then a summary of the results of two surveys, one in February / March 2022 and a second in May 2022. Due to anonymous responses, it is not possible to know if the same or different students responded to both. However, the Likert data are similar and there is little difference between these data. T-tests of the results for each question confirm there is no significant difference between the groups ($p < 0.001$). Consequently, the data have also been combined and broadly similar results are seen. The written responses, beyond the one- or two-word answers, are different between the surveys, but again, express similar sentiments. The results are followed by a brief discussion, which will be expanded in Chapter 5.

Questions

The questions used in the survey are set out here (an example of the survey is given in Appendix 6):

QS1. Thinking about you experiences with animations / simulations / virtual laboratories; do you learn more about the principles of scientific inquiry from these than from physical laboratories (inquiry).

QS2. I gain more of an understanding of theory through practical experience using real rather than animations / simulations / virtual laboratories (theory).

QS3. Virtual laboratories teach me more practical skills, such as measurement and observation, than I learn in a physical laboratory (practical skills).

QS4. I feel more motivated and engaged using a physical laboratory rather than a virtual laboratory (motivated).

QS5. I develop higher level skills and attributes, such as, communication, teamwork and perseverance; when using a virtual laboratory rather than a physical laboratory. (higher skills).

Results

Table 24 showing student survey data collected in February and March 2022. Refer to text for the details of the questions

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
QS1. Inquiry	1	2	7	3	2
QS2. Theory	6	6	1	2	0
QS3. Practical skills	1	1	6	3	4
QS4. Motivated	6	4	3	2	0
QS5. Higher skills	0	1	2	5	7

Table 25 showing student survey data collected in May 2022

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
QS1. Inquiry	1	3	6	8	1
QS2. Theory	5	5	4	3	2
QS3. Practical skills	1	3	6	4	5
QS4. Motivated	4	5	6	4	0
QS5. Higher skills	0	1	2	9	7

Table 26 showing student survey data collected in February / March and May 2022, combined

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
QS1. Inquiry	2	5	13	11	3
QS2. Theory	11	11	5	5	2
QS3. Practical skills	2	4	12	7	9
QS4. Motivated	10	9	9	6	0
QS5. Higher skills	0	2	4	14	14

The Likert response data are shown in Tables 24 to 26. These have been simplified by rearranging and combining the results to show positive and negative attituded to VL for each question. Strongly agree and agree are combined to give one value, similarly, disagree and strongly disagree combined to give another, the modified data are shown in Tables 27 to 29. The final data set are also presented graphically in Figure 23.

Table 27 showing simplified student survey data collected in February and March 2022

Question	Positive for VL	Neutral	Negative for VL
QS1. Inquiry	3	7	5
QS2. Theory	2	1	12
QS3. Practical skills	2	6	7
QS4. Motivated	2	3	10
QS5. Higher skills	1	2	12

Table 28 showing simplified student survey data collected in May 2022

Question	Positive for VL	Neutral	Negative for VL
QS1. Inquiry	4	6	9
QS2. Theory	5	4	10
QS3. Practical skills	4	6	9
QS4. Motivated	4	6	9
QS5. Higher skills	1	2	16

Table 29 showing simplified student survey data collected in February / March and May 2022, combined

Question	Positive for VL	Neutral	Negative for VL
QS1. Inquiry	7	13	14
QS2. Theory	7	5	22
QS3. Practical skills	6	12	14
QS4. Motivated	6	9	19
QS5. Higher skills	2	4	28

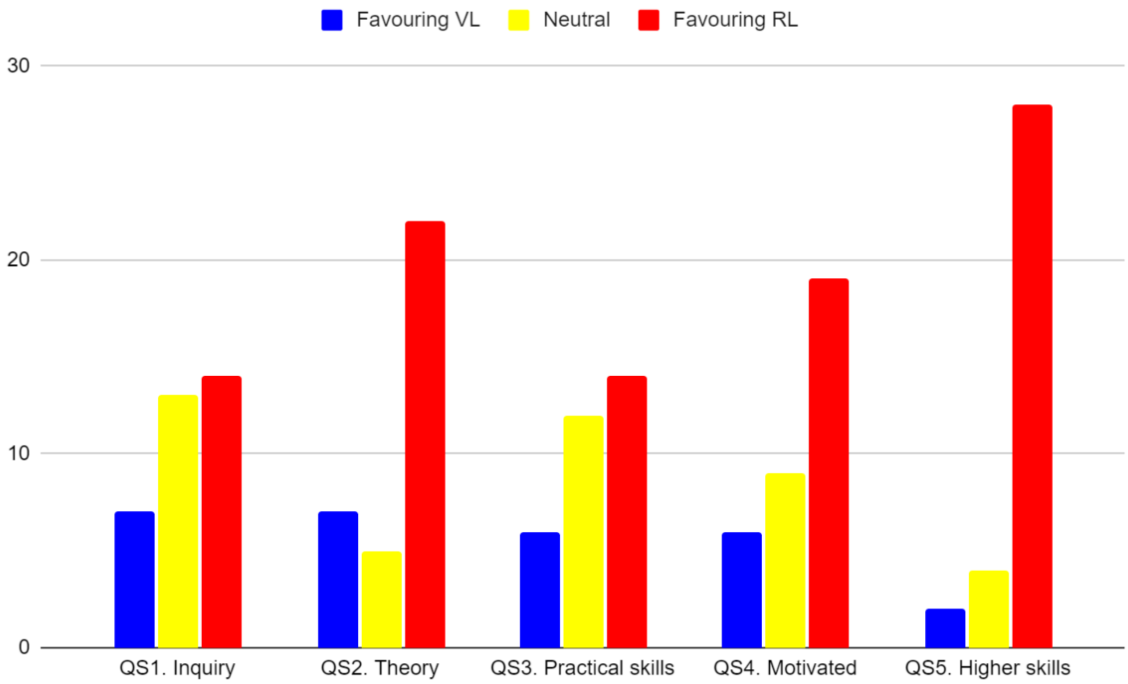

Figure 23 showing the simplified student survey data collected in February / March and May 2022, combined.

Although not everyone added written comments to their evaluations, where these were recorded, they provide additional information. This is useful in giving the reasons for a choice and are more balanced than the pure numerical data would indicate. Due to the fairly specific nature of the questions the responses are not very wide ranging but following the spirit of the method set out by Nowell et al (2017), see Table 22, some themes are found to emerge. Much of the work described by Nowell et al (2017) is relevant to a large project with a number of co-workers, my small, single-handed project requires a simplified approach but still needs to retain the rigour of the method.

The themes can be broadly categorised as: Hands-on, Doing it myself, Method, Theory. I will give a little more detail about the responses, which relate to these:

Hands-on: 'only properly learn about physical components in an experiment if I do them in a physical lab'; 'practical gives us a hands on experience'; 'hands on experience and being able to interact with the experiment helps you understand better'; 'in a physical laboratory I am able to practice and preform measurements and observations myself so therefore pick up more skills than I would in a virtual laboratory'.

Doing it myself: 'I would rather measure using my hands instead of using a program that will do it for me'; 'you learn more by experiencing it yourself'; 'doing the actual thing myself helps more'; 'doing the work myself, in real life and it gives me more experience'; 'because its different from doing it by yourself in real life than virtually'; 'I'm doing the experiment myself in a real lab'.

Method: 'virtual laboratory focuses more on the method rather than skill'; 'Real because it lets me remember what I do and the steps better'; 'virtual labs, you can use different equipment and different elements that are too expensive / too dangerous to have in the lab'; 'decreases the probability of error and is a accurate demonstration'.

Theory/knowledge: 'virtual laboratory goes into the theory in more detail'; 'virtual laboratory helps quiz our knowledge'; 'virtual labs are more helpful in terms of theory work'; 'virtual laboratory it asked you questions which helped understand and get the practical right'; 'With virtual labs ... you can also visualise parts of the experiment that can't be seen in a physical lab'; 'I can visualise what I have seen physically and virtually to better understand the theory side of the chemical process'; 'the virtual laboratory helped to quiz our knowledge on the practicals'; 'more understanding in physical laboratories as it helps to see what I am doing properly'; 'virtually it's asked us questions which was really good'.

Discussion

While the data are limited and from only a small sample, there are some features which seem to be clear. While not a statically representative survey, it is indicative of the students' experience and helps to guide the questions and discussions in Phase 2 of the study.

So, what can be gleaned from the data? When looking at the Likert results there seems to be a clear preference for the physical laboratory, over VL, for all of Holman's (2017) criteria. This seems to be particularly the case for QS5, where students feel 'I can't work in a team in a virtual lab' and 'you need to communicate in person'. They believe that they 'develop higher level skills in a physical laboratory as [they are] able to p[er]form in a group where communication is key to p[er]forming a successful practical. Whereas with virtual laboratories [they are] often working alone … so teamwork and communication is not required'. Similarly, that they 'develop teamwork … working with people physically, which increases communication', whereas 'it is more of a one person task when completing the experiment virtually'. Students also feel they 'gain more independence and attention to detail' and are 'better as persevering because anything can go wrong in a lab, whereas in a virtual lab, most things turn out as they should'.

There are similar comments in the other responses, and these are grouped in themes above. Generally, these favour the physical laboratory in agreement with the Likert data. The themes of 'hands-on' and 'doing it myself' which seem to emerge, are related to the ideas of 'presence' and 'agency', discussed in Chapter 1 (see Figure 1) and relate to RQ1 and RQ2. Students identify that the quality of the interaction is different in the VL, they are identifying that there is a different type of learning when interacting with physical objects compared to that in the virtual world. They 'learn more by experiencing it' themselves, being present in the performance of 'measurements and observations' 'and being able to interact with the experiment helps' better understanding. Students also value that they are 'doing the experiment myself in a real lab'; they have control by 'doing the actual thing myself'.

The other two themes which appear, 'method' and 'theory / knowledge' relate more to learning and RQ3; these concepts are explored in Chapter 3. Students seem to identify the value of the VL which helps them 'to do it step by step and understand the method' with 'questions which was really good'. However, they still favoured 'doing it in person, you get to learn through actual experience' and feel they 'pick up more skills than [they] would in a virtual laboratory'. An advantage with VL is 'you can use different equipment and different elements that are too expensive/ too dangerous to have in the lab', but you lose the feeling of being 'excited to do the work in a physical laboratory'. Some students find 'simulations and virtual labs are more helpful in terms of theory work' as 'you can also visualise parts of the experiment that can't be seen in a physical lab', while for others 'doing the actual thing myself helps more'.

In summary, students seem to appreciate the extra perspective the VL provides, the clear methodical presentation and opportunities for questions to check understanding. However, they largely prefer working in the physical laboratory, which is more engaging, offering the opportunities for developing hands-on skills, teamwork, communication and 'because its different from doing it by yourself in real life than virtually'.

So, in terms of the research questions:

RQ1: students do appreciate a difference between the laboratories and feel they would prefer to be working 'hands-on'.

RQ2: students appear to trust the results of the VL, which 'decreases the probability of error and is a[n] accurate demonstration' and where 'most things turn out as they should'.

RQ3: students appear to value learning in the VL which help them 'to better understand the theory side of the chemical process', allowing them to 'visualise parts of the experiment that can't be seen in a physical lab' and by asking 'questions which helped [them] understand and get the practical right'.

Phase 2 data

Introduction

The data presented in this section were gathered in interviews with students during the first 4 months of 2023. The interviews were recorded and transcribed as described in Chapter 3. After completing the transcription and checking of the data, I listened to the recordings and read the transcripts several times to follow Nowell et al (2017) process of 'Familiarizing yourself with your data' (see Table 22 for details of Nowell et al's method, relevant to this section). The next phase is 'Generating initial codes', which I did by looking for patterns and key words in the data. My Phase 1 results gave me some ideas for codes/themes and others developed as I reviewed the data. I tried using codes to identify parts of the data, but I found this cumbersome and unsatisfactory. I therefore decided for my relatively small data set that it would be easier to separate the text relevant to each emerging theme. I therefore set up tables for each of my themes and the three research questions, then copied relevant responses into the tables. A separate section was used for each students' response, except in the case of the joint interviews where sometimes an exchange would involve both students. I decided not to separate these by student as the exchanges were often informative (as will be shown below). This corresponds to Nowell et al's 'Searching for themes' phase. As I am the sole researcher on this project, I carried out the 'Reviewing themes' myself, where ideally others would have brought a greater range of perspectives to the task. As Heidegger (in Hanson, 1962, p. 24) points out 'Every inquiry is a seeking. Every seeking gets guided beforehand by what is sought', so my review of the themes, which I have already identified, really yields nothing new. The process of 'Defining and naming themes' does have the advantage of clarifying what the difference is between some aspects. For example, in this work the **hands-on / reality** theme is to do with the students' presence in the moment and activity, while the **doing it myself / control** theme is related to the students' agency and freedom to make choices (see discussion in Chapter 1). I have had some difficulty in separating the crossover of these themes, but for me they are distinct. Nowell et al's (2017) final phase is 'Producing the report', which is what you see here.

The next section gives some more specific information about the interviews, building on the information supplied in Chapter 3. This is followed by the results of the thematic analysis, which are presented separately for each theme and research question. There is some overlap in the material which could address different themes and research questions. In selecting and arranging the material, I have tried to follow Connelly and Clandinin (1990) who 'identified apparency, verisimilitude, and transferability as possible criteria' for guiding qualitative inquiry. I hope that the material helps to show students 'both living their stories in an ongoing experiential text and telling their stories in words as they reflect upon life and explain themselves to others' (Connelly and Clandinin, 1990).

Interviews

The student interviews were carried out as described in Chapter 3. As a practitioner researcher and the past teacher of the students interviewed, the interviews were more conversations of shared experience than would have been the case for an external researcher. This has the advantage that the students are more at ease and comfortable talking; but has the danger that I might directly influence their responses, or they may modify them to say to what they want me to hear. Having said that I am part of their experience of chemistry and VL, so have an indirect influence anyway. In an attempt to balance this, I am deliberately including some of the questions or comments I made during the interviews so that others can judge how much I affected the conversation.

Two of the interviews were (at the request of the students) conducted with two students simultaneously. Although, at first, I was uncertain how this would work, the results were effective. The students entered into conversations between themselves which I feel drew out deeper material than I might have gained individually. In particular, the interview including students F and G, is particularly fruitful and provides a lot of interesting material. In a way this interview could provide a comprehensive answer covering most of the research questions, however, I am conscious to allow other voices to be heard as well. In reporting the interviews, I have distinguished the *spoken words* of the students and myself as interviewer by using *italics*, rather than inverted commas, which can become cumbersome.

Thematic Analysis

This section is divided by theme, and each is considered separately. The results for each of the research questions are then reported. Inevitably there is significant overlap in some material and so I have attempted to provide a mixture of the 'demonstration mode…[where] data tend not to speak for themselves but instead are used in exemplary ways to illustrate the thoughts of the narrative writer… [and the] inductive mode, [where] data more clearly tell their own story' (Connelly and Clandinin, 1990). To this end, the themes have been allowed to emerge through longer sections of material and dialogue, providing the 'thick description' recommended by Lincoln and Guba (1985, p. 316) and Nowell et al. (2017). This will hopefully allow the reader to better judge the transferability of the conclusions to the research questions and increase the trustworthiness of the study. The research questions, themselves, are then addressed using a more demonstrative mode, focusing on the points salient to the specific question, and illustrating these with examples from the themes. This inevitably results in some material appearing in both sections, but I have tried to minimise this as much as possible without detracting from the arguments.

The themes which have been identified during the interviews include those which appeared in the questionnaire responses, with two additional themes, trust and consequence. The themes are briefly described here, before the responses are reported.

1. **Hands-on / reality** – this is the idea of being in a real world, where items can be touched and held. This is the concept of presence, being engaged in the experience.
2. **Doing it myself / control** – the idea that you have influence on the situation your actions cause things to happen. This is the concept of agency, being able to influence the experience.
3. **Method / skills** – this is the practical aspect of the activities, how things are done, practiced, sequenced and how skills are learnt.
4. **Theory / knowledge –** the theory, knowledge, understanding which is gained and the more abstract competences.
5. **Trust / truth** – the belief in the world they are part of, the verisimilitude of the experience, how the 'quality' of the truth is determined.
6. **Risk / consequence** – the things which follow from actions, the results which flow from decisions, in particular the possibility and consequences of failure.

T1. Hands-on / Reality

STUDENT G: *Although I enjoy the theory side of science. I feel like having the practical side of it makes it feel more, it makes it feel more real and it makes it feel more, I don't know the word, like enjoyable.*

STUDENT F: *yeah. I am a hands-on learner.*

STUDENT G: *Yeah.*

STUDENT F: *See, I would rather do that with the theory cos it helps me learn the theory type in a way. So, I, I like the hands-on approach. I, I always have throughout like,*

STUDENT G: *yeah, I guess it's like if you ask a chef to learn to be a chef without cooking, it's like, because science is so hands-on, it relates to everything around you not applying that and not actually going through that yourself.*

The students feel that practical science is an essential part of their learning, fundamental to their learning. One now asks:

STUDENT G: *Would you actually be a scientist?*

STUDENT F: *Yeah.*

STUDENT G: *Because although you know the theory, you can't apply it. It's like if it's like doing your driving theory test doesn't mean you can drive*

STUDENT F: *literally,*

STUDENT F: *literally*

STUDENT G: *you know what I mean?*

STUDENT G: *You could get full marks on that, but you can sit in a car and not know how to drive. I kind of think it's like,*

STUDENT F: *see, so you could explain the whole of chemistry, but you can't*

STUDENT G: *Exactly.*

STUDENT F: *You can't do it.*

STUDENT G: *If someone said like, do a reflux, you could tell 'em the whole. Like step-by-step routine of how you do it. You give them a, like a Quick-Fit set and they look at it and they go, how do I stand it up?*

These students feel that without the embodiment of their knowledge in practical activity, the theory they learn is of no use. Extended extracts from the student interviews focused on this theme are given in Appendix 8 and these are referred to in the discussion, below.

The above dialogue sets the scene, for these students – *science* is *practical science*. They view the experiment as the way science is done, … *'because science is so hands-on'… 'although you know the theory, [if] you can't apply it' … 'would you actually be a scientist?'.* These ideas are found in other student comments as selection of which are given here: *'The practical side of it makes … it feel more real'… 'you can like touch it' … 'it's actually there'… 'you know it's real'.* What is it that real feels like? … *'you see all the process in front of your eyes, so even you can feel the temperature, you can see the colour change, everything … it's engaging you completely like all your sense, and you feel more* *confidence when you do the experiment, when you finish because you feel you learned all this, and you saw the experiment'.* The students are engaged they feel present in the moment *'seeing things in my own eyes … what's in front of me'.* They feel there is *'a difference between doing it in real life and doing it [virtually], you don't really use the same skills. You don't practice the skills that you use in real life… it's mainly the manual dexterity part of it, you don't practice that'*.

T2. Doing it myself / Control

Appendix 9 gives extended extracts from the student interviews which are focused on this theme. Students feel that the VL is an environment where there is a lack of agency, *'sometimes it kind of like does it for you. So, you [are] kind of just sitting there and watch[ing]'.* They sometime feel they do not have control of the situation and 'q*uite a lot of the times … it feels like they direct you somewhere'… push[ing] [you] towards getting the right answer'.* The VL *'goes through … in the most like, efficient way …. It tells you what to do, as you're doing it'.* While '*sometimes getting [it] wrong and getting the wrong results is kind of good in a way… then you learn from it next time'.* The VL constricts their choices allowing only '*certain measurements'* and sometimes it feels like '*would I actually have got that?... I'm a bit unsure'*.

In the real laboratory there is more opportunity to *take 'the leader role… being more organized, making sure your equipment's in the right area'* and *'it is easy to control the measurements and just how, we take data and things like that … in terms of studying, I just prefer … the physical lab because it's easier to understand how things actually work and how to control things better… I gain more skills through the physical life… it feels [when] actually doing the experiment [I am] more in control … it's easier to see how things are actually being done'.*

However, the VL does also give control to the students to choose the time and place of their learning; '*… we did the practical, but we can also like kind of redo [it] at home. I do like that. A sense that I know that, yeah, I might have done it a few months ago, but I can go and do it at home whenever I want'*. That is a real advantage to this student, who '*can't set a lab up at home'*. For another *'it's much easier than doing the practical again to just quickly hop on a computer or your phone, carry it out, and then it's back in your head'.*

T3. Method / Skills

It appears that students value the skills they develop in the practical laboratory and see these as different to those they develop in the VL, this is expressed in the extended extracts given in Appendix 10. In particular, the skills they believe they gain in the practical laboratory are such things as:

STUDENT C: *…doing things more carefully and accurately, like measuring something or when having to repeat a process …'*

STUDENT D: *… Many skills … mostly safeties, Hazards, … end pointing of the acid and the base … measuring also … how to use your hands to process the experiments, so like [making] measurement.*

STUDENT A: *With a real lab, you actually learn teamwork skills as well … like communication. Whereas, if you're just doing it individually, you're not gaining anything out of that, you're not talking to anyone or helping people out … In our labs there's tons of other people in there as well, so you've got to be careful about being with around other people, making sure everyone else knows what's going on*

STUDENT C: *… in practical one, it's like skills, you gain it … skill about like how to take exact measure from pipette or use dropper and all these things.*

STUDENT D: *… you cannot imagine them or … think about them unless you do it in practical ... Otherwise, [if] you want to learn them, you don't know the reasons of it.*

Students do not see these skills being developed in the VL. While *'the virtual laboratory is easier in terms of understanding things – mathematically. The physical laboratory is easier in terms of understanding how things actually work and how to use the equipment.'* So, the VL does not give you all the skills needed in a laboratory; *'… in practical one, it's like skills, you gain it. But in virtual one, there is no skill, you just need to follow the process and know the theory …'. Also 'some things … you cannot imagine them or … think about them unless you do it in practical ... Otherwise, [if] you want to learn them, you don't know the reasons of it.'* Similarly, in the VL '*you don't really use the same skills, you don't practice these skills that you use in real life … it's mainly the manual dexterity part of it - you don't practice that…'*

However, they do see value in the VL as providing either an introductory guide or as a revision source. There is a '*step by step how to do it'* which help students who have a lot to think about in the potentially confusing real laboratory, as '*everything is already there for you to have … a smooth practical, before you do it in a lab'.* The VL has a structure which '*kind of guides you through it… is it more in terms of understanding the practical and just going through it in order to get it…'. 'It's more of the actual how to do the practical that helps … cause like you might forget to do something'* and *'sometimes you learn some tips'.* Then after the practical '*doing virtual labs is a good reminder for practical':* the VL provides a revision source as well.

So, students do not see the VL as a replacement for the real laboratory – *'you tend to pick up more with an actual … practical lab because it's a lot more hands on';* but they do see it as complementary, *'… it helps you learn, and it definitely helps you practice … [you] are practically able to do that easily, you usually have the comfort of your own home, set up quicker. It's a good value you get out of them'.*

T4. Theory / Knowledge

The extended extracts from the student interviews focused on this theme are given in Appendix 11 and are explored in more detail here. The practical aspect of science is seen as helpful by the students when trying to learn and recall theory. They feel '*it's like better even for memorising cause you saw … everything'* and *'you remember because … you create links in real life. Like, I've done this, let's link to this'.* Learning theory seems to be an area where the VL provides some similar experiences to the real practical.

INTERVIEWER: *… [do] you think differently in the real laboratory and the virtual laboratory? …*

STUDENT E: *I'd say they're, they're quite similar, cause you're still thinking about the reaction, you're still thinking about the same process that you know, or that you don't know if it's a new reaction. There is certain more aspects in real life, cognitive thinking of what you're actually doing with your hands, but I'd say it's quite similar.*

The VL can provide an additional learning route for ***STUDENT G:*** *… I think like using virtual labs more and more can be used for extra resources and extra revision and solidifying it.* While, for ***STUDENT E:*** *I think for a virtual laboratory to be really successful [it] has to integrate a lot of elements such as like colours or stuff that makes you remember … dunno exactly what the techniques are, but I think you remember because … you create links in real life. Like, I've done this, let's link to this and that's how you remember it. I feel like there needs to be an aspect of this in [the VL].*

However, some students feel that it is the *'experiments we've actually done that … solidifies the theory'* and that *'when it comes to an exam … you've seen it, you know what it is, so you can then describe it in a way that … can still get you marks'.* In this sense the VL is an embodiment of theory, '*because you can physically see the theory behind an experiment like you can see the particles'.* This is recognised by some students '… *I would say the theoretical part is still there [for the VL]; it's just the practical side [missing]',* as a different experience. There is a sense of practical theory, perhaps similar to the Aristotelian concepts of phronesis and praxis; which is examined further in Chapter 5.

T5. Trust / Truth

From the interview data, given in the extended extracts reproduced in Appendix 12, there seems to be four different aspects of trust or truth which emerge. These relate to both the real and VL: this section focuses more on experience in the VL. There is an implicit belief in the accuracy of the VL, in which students say they *'strongly believe'*. They feel that in the real world there is *'human error. That's the problem'.* This translates into confidence in the VL; when questioning students further this seems to come from four factors:

Firstly, the quality of the source of program: '*It's from universities, probably or some professors or doctors'* or *'it's [from a] big website with credibility' or from 'people who they had experience and experts … they tried that experiment before, so they know and they expect what it should be',* also *'I feel like virtual labs will probably be developed by scientists who've been doing it a lot of years;*

Secondly, a trust in natural honesty and scientific integrity: '*I always think that like people who would make the programs or people who would input the information, what reason do they have for it to not be right?'* and because it *'was made by scientists, so it's accurate' and 'what would be their game? Especially a scientist, you always wanna get the best end result'.*

Thirdly, trust is related to authority; students tend to believe what their teachers tell them – '*you've got a status above us, so we kinda believe ... You've got like a higher authority than us … whatever you say, we go – Okay' 'and if my teacher directed me to it, then I believe the teacher to be right'.*

Fourthly, empirical evidence gained by the students themselves – '*what I've done on the virtual laboratory, it's kind of this; this equals what's been happening on when we do the experiments'* and '*because I follow the right steps and compare results with the people and the virtual laboratory, and it seems accurate'.*

These points will be discussed further in Chapter 5, relating them to some of the theoretical perspectives developed in Chapters 2 and 3. However, the trust is not universal one student felt *'sometimes it's [a] computer you don't trust box'* they are not sure of what is going on inside the 'box'. However, they continued *'they probably, they use AI, so it's more accurate. I think it's more accurate than practical*', so they still feel the computer is right. For some though, there is though still a belief in empirical evidence, a student felt if *'I was more qualified and I was an actual chemist or scientist who knew what they were doing, a thousand percent, then I would trust my results, but at the stage, we're currently at … with the resources we have as well'.* In this case, it is perhaps not confidence in VL, but a specific lack of confidence in themselves, which means they trust the results of the VL more.

T6. Risk/Consequence

In the extracts from the student interviews given in Appendix 13, we see that students have a feeling that there needs to be the 'right to fail'. If the only possible outcome is success, then there is little motivation. Chemistry, unlike most other academic disciplines can have real consequences, failure can result in serious injury – even death. Students recognise that *'risk is a really big factor … between the lab and the virtual. You've got so many risks that could go wrong', 'You take it more … seriously … you've got to …[If] something goes wrong … you don't know what the outcome's gonna be'*. So, there appear to be two factors here, firstly, related to causality, in the multi-factorial environment of the real laboratory we cannot be sure of what will happen. Whereas, in the VL *'it is like set rules, so you can't really make a mistake',* so *'it feels very much like you can just kind of click [to] do the steps'.* The second factor is the consequences themselves: in the real laboratory *'if it goes wrong … instead of just doing the level, you've got do say's two hours practical work' 'or if there's a solution that stains your skin. If it says that on virtual, then it's, oh, well it's supposed to stain my skin, but it's not cuz I'm not actually using it … or if the glassware breaks, it's not really gonna break on there … anything bad that happens in a lab is not really replicated on it'.* So, the real laboratory *'engages you more, because you have to think about the … consequences of your actions … [whereas in the VL] it's not actually happening … it's just on the screen'.*

THE RESEARCH QUESTIONS

The student responses analysed by theme are now reconsidered with the aim of answering the research questions. I have tried to avoid repeating the material given earlier by selecting responses which provide the best fit to theme or research question – you may have a different opinion – and this has been a subjective choice – where I have tried to provide the best narrative. Each of the research questions is addressed in turn.

RQ1: The extent to which students experience learning in a virtual laboratory as a mirror of reality?

This question has different answers for each student and the responses change as they consider different aspects of the VL. Broadly, I have set out those which show a closer connection between the two laboratories first.

Comparing the two laboratories, Student C feels – '*I can get the right results in the virtual laboratory. Same [as the real laboratory], but if I don't get it, it kind of guides you through it'.* They see an enhancement using the VL. Similarly, Student A says – '*because you can physically see the theory behind an experiment like you can see the particles'.* The students seem to see the VLs that they have used as a version of reality, for Student A – '*…some things are similar, like the chemistry'*, while for Student D – *'some part, it's the same, like the reactions and what you do – Same – You expect same things … You still feel happy, but it's not like 100 % because if you doing it practically [it] feel[s] different'.* Considering the thought process, then for Student E – *'I would say you do think about the process you experience in your mind; you experience doing this same motion or pouring this substance… I'd say they're, they're quite similar … you're still thinking about the reaction, you're still thinking about the same process that you know, or that you don't know if it's a new reaction'.*

When Student B looks at the VL they feel that – *'If it were just a picture, then no [it is not the same]; but … the virtual lab, it just explains what it is usually and what it does, it's not bad'.* Is thinking in the VL different? Student B feels that it is – '*Probably not different … you just have to think more in the real one'.*

So, students appear to feel that the VL does provide a similar experience, but they recognise this is not the whole picture and they tend to focus on the differences; these fall roughly into five different areas (closely matching the themes identified above:- Presence in T1; Interactions in T1 and T2; Motivation and Control in T2; Consequences in T6):

Presence

For ***STUDENT F:*** *… it doesn't feel like, oh, I'm in the lab type of thing.* There is agreement from ***STUDENT G:*** … *definitely doesn't feel quite the same, it's not going to, because obviously you're just looking at it kind of one dimension.* It does not feel real for ***STUDENT B****: … because the virtual one you're sat there staring at a screen.* While ***STUDENT C****: … like[s] seeing things [with] my own eyes. … when I see something act when I'm doing things or watching someone do it in an actual lesson, it's easier to understand because … I'm seeing how things are … playing out in front of me rather than just reading, … and watching a video and clicking buttons …*

For ***STUDENT D****: … the practical … [the VL] feels similar to that. … if I give a rate, it's gonna be like 5 out of 10 … in between… [while] some things … you cannot imagine. … The practical one, when you see all the process in front of your eyes, so even you can feel the temperature, you can see the colour change, everything from closely … it's engaging you completely like all your sense … but in virtual one is less realistic.*

There is a suggestion from ***STUDENT E****: … I think for a virtual laboratory to be really successful has to integrate a lot of elements such as like colours or stuff that makes you remember …*

STUDENT F*: … when you're actually, they're doing it... making sure you're doing it right more. You're more conscious ...* ***STUDENT G:*** *Definitely ... I think you take a very different approach to it.*

Both Students F and G also study psychology and were asked to consider cognitive processes, in the two laboratories. ***STUDENT F**: … a lot of the time we talk about schema … like little mental shortcuts. I guess we kind of do make these shortcuts; and then in the lab you might think, I've done this before, see made the shortcuts, so then you just can do automatically.*

***STUDENT G**: I feel like you have to think a lot more like in depth about a practical lab. I feel like when you're doing it virtually, you can kind of just cruise through it, you're not necessarily taking all the information in, you're not necessarily processing at all. Whereas, I think with the practical lab, you're thinking a lot more about each step and you're kind of taking in more and processing it.*

***STUDENT A**: in our labs there's tons of other people in there as well*. While individual interactions are also important for ***STUDENT C**: … if I don't get anything, I can just ask [another student to explain things] … for me; online it's harder to do that.*

Interactions

***STUDENT A**: … with the virtual labs, you're literally just dragging and dropping something and just moving things around on a screen, whereas in real life, you literally have it in your hands. **STUDENT B**: … touching stuff … is all connected to your brain. So, it kinda triggers like, oh, I know what that is, type [of] thing. Where if you just touching like just the keyboard, then it's just like that's all.* For ***STUDENT D**: … the practical [shows you] how to use your hands to process the experiments.* While the feeling for ***STUDENT C**: [is] the physical laboratory is easier in terms of understanding … how to actually use the equipment.*

***STUDENT E:** … you don't really use the same skills. You don't practice these skills that you use in real life … [and] cognitive thinking of what you're actually doing with your hands.*

***STUDENT F:** … you don't have the hands-on approach*

***STUDENT G:** … It's not got the, you're not picking things up yourself, finding which one is it kind of directs you to things … a practical lab because it's a lot more hands on. You know, you're getting the equipment yourself. It, it takes longer. It feels a lot more like you're actually doing it. Whereas the virtual one, I think's just always a bit, it does feel like you're doing it, but it's nowhere near got the, the feel of the actual lab.*

Motivation

***STUDENT A**: … in real life … I think it's more engaging. **STUDENT B**: I think it engages like your brain more … a lot of people aren't engaged cause they're just staring at screen.*

***STUDENT E: …** there's no consequences to get it wrong … I feel like I'm more careless … it feels like I'm not really engaged.*

The following dialogue highlight physical presence in the laboratory which can involve particular actions and clothing not normally found outside the laboratory …

***STUDENT G:** Yeah. Like it feels more like rewarding when you do it practically,*

***STUDENT F:** I guess in a way. Like you feel, I don't wanna say it like, like a scientist.*

***STUDENT G:** It feels real … I'm gonna wear a lab coat and I'm gonna do all these practicals. It feels more fulfilling to do it in person rather than – like you, you could literally be sat at home in bed doing the virtual one … It makes it more real in your head … I'm putting on this lab coat, people around me* *are gonna think I know what I'm doing, so let's make it look like I know what I'm doing. Let's do it right. Let's do it. Let's get the results I want.*

STUDENT F: *it's a bit like, I dunno, you always like stereotype – the goggles and the lab coat. I think it's kind of nice to, like, you'd be able to put it on and be like, ooo,*

STUDENT G: *… you put it on, you[r] like, yeah, I am a scientist.*

If you were not working in the real laboratory, then for ***STUDENT G:*** *… I don't think it'd feel as fun …*

Control

Students say they do not always feel they have control in the … *(**STUDENT A**:) virtual one, a lot of the times the steps are just on screen, and you just have to … move this to here and I need to mix that with that.* For ***STUDENT C:*** *the physical lab … is easier to understand how things actually work and how to control things better.* ***STUDENT D:*** *… in practical one, it's like skills you gain … but in virtual one, there is no skill, you just need to follow the process …* Similarly, in the VL for ***STUDENT E:*** *… everything is kind of guided and everything makes sense … but there's a bad side … because you're not really getting a hands-on experience, and sometimes it feels like you don't actually know what you're doing.*

Consequences

STUDENT A*: … If it says that on virtual … it's supposed to stain my skin, but it's not cuz I'm not actually using it … It's just anything bad that happens in a lab is not really replicated on [the VL] … you are just looking at a screen … that's not bothering me.* However, *… in our labs … you've got to be careful about being with around other people, making sure everyone else knows what's going on*. ***STUDENT B****: … if you actually make a mistake in real life, it's gonna affect you.*

STUDENT E*: … You just putting colourful substances with colourful substances, and you don't actually know what it is; there's no consequences to get it wrong either.*

STUDENT E*: I feel like the consequence feels a lot more severe when you do it … I've just spent three hours doing this, I've put the wrong chemical in, I've got, start again. Whereas on [the VL] you just press undo … you can just kind of click … the steps. It feels a lot more … comfortable to do it that way, whereas when you're actually doing it yourself … you feel pressure …*

The real laboratory feels more risky for ***STUDENT F****: … it feels more real, you take it more … seriously … [if] something goes wrong … you don't know what the outcome's gonna be … the risk is a really big factor between the two… so many risks that could go wrong, whereas the virtual.* ***STUDENT G****: … it's like the consequences; it's like if I do it wrong on the laptop, you can just redo it. Whereas like doing it in real life, it's a lot harder to redo it. It takes a lot more time* ***STUDENT F****: … So instead of just doing the level you've got do say's two hours practical work.*

STUDENT G*: … I feel like it means a lot more to you to do it in the lab. In a way it feels a lot more rewarding because you've only got that kind of one chance when you do it right. You think, actually, I really enjoyed that outcome. You know, you tend to remember it more when you really enjoy it.* So, for this student the risk is part of what makes the experience real, something they do not feel they get from the VL.

In summary, students appear to view the VL as a factual, but not an emotional mirror of reality. They feel that the science, the chemistry, is reproduced in the VL and that the results they obtain are similar to the real laboratory. However, there are a number of elements missing from the experience; these will be different for each student. For the students interviewed in this study a number of elements have been identified including: presence in the experience; interaction with physical objects and other people; motivation to be involved in the learning experience; control of the course of the experiment and the risk or jeopardy of being involved in a live, possibly unpredictable event with real consequences. In Chapter 5 these factors are examined in the light of the work of Sennett, Kuhn, Hanson and others.

RQ2: The extent to which students regard the results of experiments conducted in these environments as trustworthy?

As shown in the section on Trust / Truth, above (and Appendix 12) most students trust the results of the VL. Student C say they – *strongly believe* – in the results of the VL, while Student E says they – *tend to believe it.* Student B says this is – *because it's from a trusted website, that probably knows more than we do.* Students A, F and G also say they would believe the results of the VL. Student F says this is because they – *have researched it, must have gone into it. They can't just kind of make this program outta nowhere with things that aren't correct. I feel like it will be checked and checked again*. While Student G feels – *like virtual labs will probably be developed by scientists who've been doing it a lot of years.* Also, for Student D – *because it's been made by probably people who they had experience and experts, so probably they, they tried that experiment before, so they know and they expect what it should be right, and we are just trainer. We train these ones, so probably make mistakes. That's why I believe virtual one is more reliable.* This idea is also developed by Student G – *I feel like I'd have to have a lot of evidence before I said the virtual programs wrong. I think it'd take a lot for me to be like, yeah, no, I don't trust it …I think you automatically presume when something's made. That there's a lot of background research. It's been like peer reviewed; people have tested it …*

Students also tend to trust the results of the real laboratory. Student A – *cuz I've actually done it … and they're the results I've got from my own experiment.* While, Student C says – *because I follow the right steps and compare results with other people and the virtual laboratory, and it seems accurate.*

For Student D – *… because … most of the practical one, when you see all the process in front of your eyes, so even you can feel the temperature, you can see the colour change, everything from closely, but, so we mainly think about the reason about the reactions, what's happening … but in virtual one is less realistic, so maybe you don't think about all the details. So, I think in practical, it's more in detail when you think about the experiment as I mentioned, it's engaging you completely like all your sense. And you feel more confidence when you do the experiment, when you finish because you feel you learned all this and you saw the experiment, so give you more confidence.*

Student G trusts more in the experience – you *were there when it happened. You are the person who … put it together … this is what you've got. Whether it's right or not, they are the results you would get cuz that's what you did …* There is also confirmation from others for Student F – *… you've got like a tutor as well … I guess it's always that like guideline of where we should be,* and for Student G – *… if you're in a classroom full of people doing labs, there's other people doing it as well. So, if you go, oh, what did you get? …*

However, there are times when students do not trust either laboratory. This distrust is not always at the surface of their thinking, but if they are questioned about what really, they think, then they are less certain.

Asked what is really happening in the VL?

STUDENT A: *I mean, technically nothing. It's just that … and you are just, you're just running it, so it's not, it's not actually there,*

STUDENT B: *That's why its virtual*

STUDENT A: *so well, exactly.*

INTERVIEWER: *What about if you did the virtual laboratory a number of times and that came up with the same result?*

STUDENT B: *No, because there, there's just a, a program, so you'll always get the same answer.*

So, students see the VL as something constructed, and asked more about the origins they start to question.

STUDENT D: *… but sometimes it's [a] computer you don't trust box and … they probably, they use AI, so it's more accurate. I think it's more accurate than practical*.

For this student although they do not know what is happening inside the 'box', they trust the VL, possibly because of the AI.

Asked to think more about why they trust the VL, then Student B would believe – *because it's like the Royal Society of Chemistry. It's like a well-known website … [if] I didn't know it, probably not.* While Student A says – *if … [it is] one from the RSC, … yeah; but if it's just this random [person] … on the internet … are the[y] right?...*

So why do students believe, why do they trust anything? It is related to what they are told… ***STUDENT E:*** *… and if my teacher directed me to it, then I believe the teacher to be right.* While ***STUDENT G:*** *(speaking to me, the Interviewer/Teacher) … It's all about like obviously you've got a status above us, so we kinda believe ... You've got like a higher authority than us, so we just, whatever you say, we go – Okay.*

STUDENT F: *I think that happens a lot … So much. I think people above us, we always kind of, they could be completely wrong, but we don't follow that because it's kind of what we've taught to follow people above us…*

STUDENT G: *it's kind of expected …*

STUDENT F: *… I think that's what it is, I think, we think that these labs are being made by these companies who obviously have people who are really high up in what they do, and they've got kind of the authority and be like, this is this, and they're like, oh, that's that.*

… And I'm like, now I'm thinking about it. How do you not know that it's just some like, 18-year-old sat in their bedroom at home, programming this thing, going I think it would be 30 centimetres cubed for the titre?

So, some students, perhaps begin to wonder, ***STUDENT F:*** *You know, I mean, how do we know that it's not just someone sat in their bedroom who's never done the practical in their life, just inputting things? How do know that? I'm questioning everything now.*

However, there is doubt in the real laboratory as well. Often it because they doubt their own skills ***STUDENT A:*** *because it's us … I've done it… if I was more qualified and I was an actual chemist or scientist who knew what they were doing, a thousand percent, then I would trust my results, but at the stage, we're currently at … with the resources we have as well…*

STUDENT B: *… you might forget to do something like, I don't know, rinse the burette out or something like that. So, it's like human error – that's the problem … we've only done it once, so you could have … an anomaly…*

STUDENT C: *… something could have happened, maybe the solution was too, dilute or something*

STUDENT D: … *we could make mistakes.*

The students seem to see the problems in the real laboratory related to their own skills, but they are also aware that they are relying on others. ***STUDENT G:*** *… because like the lab techs are great, but how do I know that they know that they're putting that in that bottle, that's that … how are they a hundred percent sure that the company is sending you hydrochloric acids? It's label's hydrochloric acid. How are you a hundred percent sure that's that … it could be mixed in with something else and you would just never know* ***…*** *Now it's making me question like, next time I do a practical – it's hard.*

Asked if the real laboratory was more reliable than the VL, ***STUDENT D: …*** *When we go to[the] laboratory [the] real one … we get some like HCl 0.1 molar … that one is not reliable also, it's … probably the stuff we got … or with different concentration … we cannot try and test all of them [to see] how they are accurate – this material we get.*

So how can you be sure? ***STUDENT D:*** *… when you repeat it three times …this time you can be like suspicious about yourself or [the VL], which one? You can be in between, but still you cannot trust yourself, because … the materials … they could be reliable or not.*

INTERVIEWER: *So, you … can't trust anything?*

STUDENT D: *Exactly. It's how it stands …*

…if base[d on] our logic … it can be like something wrong [with the] stuff you have, or maybe in the computer in the system … people make mistakes, it doesn't matter [whether] it's in real or in virtual

INTERVIEWER: *… how would you try and resolve that?*

STUDENT D: *Well, researching and try to use websites like. Articles to find out … what the results should be, results, so we can try.*

INTERVIEWER: *… then you are looking for the right result?*

STUDENT D: *Yes. Well, it depends, if you working in [a] very high standard lab, it's … different. You are more reliable in [our] College, there is some points that maybe you have to consider again.*

Student D appears to believe that there is a 'right result' which can be discovered. This also seems to be the view of Student E.

INTERVIEWER: *… [if] you redo your real laboratory results, you repeat it maybe four or five times. You are getting the same result in the real laboratory, and it's different to the virtual laboratory. Which do you believe now?*

STUDENT E: *… I'm gonna be sure I've done something wrong then … something systematically wrong that I keep doing wrong. Maybe I keep adding the same concentration or something [like] that. I* *definitely ask somebody [with] more knowledge … or maybe I'd assume … I've done the wrong reaction on the virtual laboratory.*

… [if] the website's got credibility and the [virtual] laboratory does, and I tend to believe that's right or there's certain aspect I'm not seeing. For example, there's an ion and I think it's, dichromate, which can be green, but sometimes it's violet; so, it could be something like … interpretation. I [would] definitely check my results before I become sceptical about the virtual laboratory.

While some students feel they are being directed towards the 'right answer'. ***STUDENT G:*** *I think … would I have actually got that in a real thing? … because it feels like they direct you somewhere. They want you to do it right eventually so you can then do all the calculations and everything. I feel like sometimes it's a bit like, would I actually have got that? Would I not have? I dunno? Sometimes I'm a bit unsure.*

As students are asked to think more about the trust they put in the VL they reflect that,

STUDENT F: *… I guess they're coming – well, we think they're coming from people who kind of been in the industry. They know what they're doing type of thing.*

STUDENT G: *… I think it kinda comes down to, I don't know if it's like just around science, but I always think that like people who would make the programs or people who would input the information, what reason do they have? For it to not be right … they have no reason to put wrong information in there. It wouldn't benefit them, and it wouldn't benefit us. So, I kinda in that way, I think actually I would trust them because why would they do it wrong? But then you never know … Especially a scientist, you always wanna get the best end result; that's always what you want. What would they gain from putting wrong information in?*

STUDENT F: *… You seem to trust with it being … looked at and looked at again, you'd think people would pick up on it if they're bit like, well, I don't really agree with these results.*

STUDENT G: *… I think if it was like completely wrong, I think it'd be obvious … like, if you were sat with us doing a virtual lab, you'd be able to pick up on it if it was wrong.*

STUDENT F: *… what would be the point in making it [up]?*

However, if the results of the real laboratory differ from the VL

STUDENT F: *I think, I'd redo it. I'd redo the practical. Say, see is it close to that result or am I still getting my result?*

STUDENT G: *I guess if you're still getting your own result, then you*

STUDENT F: *… go back to the lab … why am I getting this? …*

INTERVIEWER: *And you're still getting the same result … different to the virtual lab.*

STUDENT F: *virtual labs wrong! … I can't keep getting it wrong.*

STUDENT G: *There's only so many times you can get it wrong.*

STUDENT F: *Or maybe like … not just you, but someone else do it as well. Cause then obviously it might be you, but if another person does, I think it's kinda like … if a group … do it, [it] is better than just one. So maybe I would question the [virtual] labs if mine kept … being right … I would question it.*

STUDENT G: *I feel like I'd have to have a lot of evidence before I said … the virtual programs wrong.*

Discussion

There appear to be two distinct paradigms that students work in. One is the real laboratory this is based on experience, physical interaction, control of the situation. That for the VL is different it is based on trust, trust that the teacher and VL provider are knowledgeable and trustworthy, this is the trust we put in experts and textbooks, not a trust in self. In this sense VL is not practical, but theoretical in nature. This idea is expanded and developed in Chapter 5 where the ideas of phronesis and praxis are examined. The work of Hanson on theory-laden observations and that of Kuhn on paradigms is also relevant here.

RQ3: The extent to which teachers can have confidence in the educational value of learning in the virtual laboratory?

Students see a number of advantages of the VL; there is a simple practical advantage that the VL provides a safe 'playground' in which to learn about practical chemistry. ***STUDENT A:*** *… if you've never done chemistry before and you want you to do an experiment, and if you're in a lab, it's like, right, I need to get these, these, these [and] what happens if something goes wrong? But at least with [the VL] everything is already there for you to have … a smooth practical before you do it in a lab.*

The VL provides an introduction a way to safely practice the experiment before entering the real laboratory. ***STUDENT C***: *… Going through it in order to get it, … but in order to do the practical ... I think the virtual laboratory is just better for preparation …* ***STUDENT A:*** *It usually explains it quite well … step by step how to do it. So, I think it's quite good … if you have no idea what you're doing, like even if you've never done chemistry before, you probably understand.* ***STUDENT E:*** *You can practice it, get it wrong a couple of times, and then if you were to do it in the real world after, you have some experience and some knowledge … [The VL will] build the confidence … to have many trials, and then … the real practical …* ***STUDENT F:*** *I think it's a good … starting point. I guess if it's something that you can't do in the lab, it can be a good way to actually be able to, instead of like kind watching a video.*

The VL provides a structure not only for conducting the experiment, but also the analysis and calculations. ***STUDENT A:*** *with the titration, especially with the Royal Society of Chemistry one, it goes through the calculations as well. So, once you've done the titration and you weren't sure of how to calculate, whatever you need to calculate. Then going through it … again to refresh your mind and then going step by step [through] a calculation, to do your own results after, that helps.* ***STUDENT C:*** *But if I don't get it, it kind of guides you through it.* ***STUDENT D:*** [*the VL shows you the] steps and the stage, and sometime in virtual, it's like [a] caption open[s] and tells you why, why you do this, why you wait, and what you hit, and notes. So, you get some tips, and you can use them in real world. Especially the steps, like which one you should do first and second. It's like, you know, which other one is like step by step. Finish one step, you go to second one.* ***STUDENT E:*** *… in virtual laboratory, sometimes there is videos to help you. Directed … to the reaction, so that's quite helpful … I think starting in a virtual laboratory is good. Helps build knowledge and … applying it in real life. That's the way I would see it to do it … I think they help you learn, and they definitely help you practice.* ***STUDENT G:*** *I like that the virtual labs, they kind of lead you through it a bit more. They're a bit more like, and then do this and do this … Instead of when you're doing it like yourself, you can't second guessing yourself. Sometimes, at least when you're doing that, you know that like what you are doing is correct, cause it'll tell you immediately after you've done it, you've done the right thing, [or] you're a little bit off. So, you can immediately see what you've done wrong, what you need to do better …* ***STUDENT F:*** *Obviously, if we do something wrong on the virtual, you kind of remember it to do it, when you're doing the actual practical, which think it's quite nice.* ***STUDENT G:*** *… Like the popups when it says like, oh, you've done this wrong try again, I think that helps you like pick up on it more.* An example of this learning is given by ***STUDENT G:*** *… I read … the meniscus from the top … I did it wrong … now every time I do an actual practical lab, it makes me think back to it, and I think from the bottom … they … clean up little things you do wrong – little things you wouldn't necessarily pick up when you're doing it yourself.*

The VL can also be a cognitive "playground" where the students can experience beyond simple reality. ***STUDENT A:*** *I think it's good because you can physically see the theory behind an experiment like you can see the particles.* ***STUDENT C:*** *It helps in terms of learning things visually … the virtual laboratory is easier in terms of understanding things mathematically. The physical laboratory is easier in terms of understanding how things actually work. I think the virtual laboratory is just better… [for] seeing how things actually work in terms of maths and equations and what's going on with the particles.*

The VL also provides a revision tool, which is appreciated by students. ***STUDENT A:*** *I think it's a good, doing virtual labs is a good reminder for practical.* ***STUDENT B:*** *It kinda like makes you remember everything that you did do.* ***STUDENT C:*** *… it helped me a lot [to] remember the process and the calculations that we had to do …* ***STUDENT F:*** *Personally, I do like it as a revision source ... I do think that handy for revision source … a backup … we did the practical, but we can also like kind of redo at home… I might have done it a few months ago, but I can go and do it at home whenever I want. I think it's a good…* ***STUDENT G:*** *... you did the practical and you were still weren't quite sure on it, you can then use that to kind of solidify it … like a second resource … you can fall back on it, if you ever need it.*

However, there are some things which students feel are better done in a real laboratory. So, in the VL … ***STUDENT F:*** *Rather than learning skill – I think it's more of like solidifying the skill.* ***STUDENT G:*** *I don't think you tend to actually learn the skill fully with a virtual lab. I think it's more you're seeing it happen, but I don't think you're learning it yourself. I think that's got to then be reinforced by like practical labs.* ***STUDENT F:*** *… I think it's more of a secondary thing. So, you do your lab first, then virtual lab to solidify what you've learned in the lab.* ***STUDENT G:*** *… like multitasking and being organized and stuff, there's not really any way to do that over a virtual lab.*

STUDENT A: *… I think with the virtual labs, you're literally just dragging and dropping something and just moving things around on a screen. Whereas in real life, you literally have it in your hands to, to do, I think it's more engaging … you actually learn, teamwork skills, as well as, like communication. Whereas if you're just doing it individually, you're not gaining anything out of that: you're not talking to anyone or helping people out.* This is also the case for ***STUDENT C:*** *… my concentration levels in the actual lab are way higher than when I'm just scrolling mindlessly and clicking mindlessly in a virtual lab … I think avoid screens.* While, ***STUDENT A:*** *I think [the real laboratory] is good for exams, because if I have a question that links to a practical we've done, then my mind goes back to doing that practical – I can remember … [but the VL] it's just another screen …*

Also, ***STUDENT B:*** *… sometimes [the VL] kind of like does it for you. So, you [are] kind of just sitting there and watch[ing], so it doesn't always go in … I prefer the real one … I think it engages like your brain more … They say a lot, within our generation, … that a lot of people aren't engaged cause they're just staring at screen. So, I think … you shouldn't stop doing things in real life, cause then everything will just turn into staring at a screen… I think you probably learn more in … the actual laboratory … you actually have to think and do it yourself, in a real one; whereas a virtual one, it just gives everything to you, so you don't have to think about all the equipment that you need.* ***STUDENT C:*** *… The physical laboratory is easier in terms of understanding how things actually work.* ***STUDENT D:*** *… in virtual one, there is no skill. You just need to follow the process and know the theory … so you don't get any skill …* Students may also, think and learn differently, for ***STUDENT B:*** *… touching stuff, like it is all connected to your brain, so it kinda triggers like, oh, I know what that is, type thing. Where if you just touching like just the keyboard, then it's just like that's all.* In the real laboratory ***STUDENT D:*** *… if you see from closely … it's different … it's like better even for memorizing cause you saw … everything*. Asked to compare learning between the two laboratories, ***STUDENT E:*** *what do I think it's different? … I would say how strong the recall is. How strong your understanding of the topic would be. If there's not elements that really focus on the group in this, then I feel like the learning will be slower or … the links will be weaker. But this can't really be generalized, because not every virtual laboratory is the same. From my experience, virtual laboratories help me when I already know the topic. It's just building the knowledge … and they definitely help you practice … if you already know it – that's the main thing.*

STUDENT G: *… you tend to pick up more with an actual … practical lab because it's a lot more hands on … it feels a lot more like you're actually doing it. Whereas the virtual one … it's nowhere near got the feel of the actual lab. So, I think doing it after [the real laboratory] just kind of tops up what you've already learned.*

STUDENT F: *I feel that, especially with doing the actual practical, I think sometimes getting wrong and getting the wrong results is kind of good in a way. So, then you learn from it next time. But that I know what you mean; just like push it towards getting the right answer.*

STUDENT G: *You did it wrong a few times … it would take you the right way the next time.*

STUDENT F: *… You don't actually learn from your mistakes … whereas in a normal lab you'd have to start all again …*

STUDENT G: *I feel like the consequence feels a lot more severe when you do it … I've just spent three hours doing this, I've put the wrong chemical in, I've got, start again. Whereas on [the VL] you just press undo.*

*I**NTERVIEWER:*** *And you compare those cognitive processes, the ones that go on in the real laboratory, how would you compare them?*

STUDENT F: *I think a lot of the time we talk about schema, don't we? Like little mental shortcuts. I guess we kind of do make these shortcuts and then in the lab you might think, I've done this before, … made the shortcuts, so then you just can do automatically.*

STUDENT G: *I feel like you have to think a lot more like in depth about a practical lab. I feel like when you're doing it virtually, you can kind of just cruise through it. You're not necessarily taking all the information in, you're not necessarily processing at all. Whereas I think with the practical lab, you're thinking a lot more about each step and you're kind of taking in more and processing it.*

STUDENT F: *I think it's like important … the risk is a really big factor … between the lab and the virtual … You've got so many risks that could go wrong …*

STUDENT G: *I think it's like a lot of like the consequences. It's like if I do it wrong on the laptop, you can just redo it. Whereas like doing it in real life, it's a lot harder to redo it. It takes a lot more time.*

*I**NTERVIEWER:*** *And do you think that helps with your learning?*

STUDENT F: *Yes … I think the fact that you kind of got to get it right. Rather than you can just redo that level … you've got one shot, … you can redo … it's the thought … I'm gonna have to come and do it and some I take a really long time – if it goes wrong. So instead of just doing the level you've got do say's two hours practical work.*

*I**NTERVIEWER:*** *Do you feel like that about exams as well?*

STUDENT F, G: *yeah.*

STUDENT F: *That is, you've got one shot. If you don't do it, then you've got to change your plan.*

STUDENT G: *You've got to then live with the consequences of that. You've then got to adapt your life, whereas you do it right*

STUDENT F: *… you're not just gonna get handed it on a plate. You've got to work for it because you know if it goes wrong …*

STUDENT G: *Like you're willing to put that little bit of hard work in. In order to just have to do it once*

I***NTERVIEWER:*** *And you feel it's the same with the lab?*

STUDENT F, G: *Yeah. Yeah.*

STUDENT G: *… I feel like it means a lot more to you to do it in the lab. In a way it feels a lot more rewarding because you've only got that kind of one chance when you do it right. You think, actually, I really enjoyed that outcome. You know, you tend to remember it more when you really enjoy it … Rather than like on a virtual, just saying, oh, I did it right. I could do it wrong and then do it right.*

STUDENT F: *… experiments we've actually done …. [I] think right, I get, it kind [of] solidifies the theory. So, you think … I've just done the actual test. So, in the exam you think, oh, we've done this before … So, I can kind of like recall it. Which is obviously gonna be important.*

STUDENT G: *I think it's good. Cause like obviously doing theory, you just kind of got the words in your head and sometimes it can get a bit mixed up. So, when it comes to an exam, say you can't quite remember the word for something, you can explain it because you can see it. You're not quite sure how to say something, but you've seen it. You know what it is. So, you can then describe it in a way that's might not necessarily be the way it's written in the textbook, but it can still get you marks.*

Discussion

There appears to be some educational value in using the VL, students value the convenience '*to just quickly hop on a computer or your phone, carry it out, and then it's back in your head'.* They also find the VL provides a useful introduction and guide for future practicals, where '*everything is already there for you to have … a smooth practical before you do it in a lab*'. This can help reduce the cognitive load on the student; '*it can be confusing in both places, although in virtual laboratory sometimes there is videos to help you direct to the reaction, so that's quite helpful'.* There is also time to think and establish methods, so '*every time I do an actual practical lab, it makes me think back to it'.* The VL *'usually explains it quite well … there's usually, step by step how to do it',* this type of scaffolding allows students to focus more on learning, rather than just managing the practical activities. Several students also see the benefit of being able to revise from the VL: '*I think it's a good, doing virtual labs is a good reminder for practical'* and '*makes you remember everything that you did'* including *'the process and the calculations'.*

Phase 3 data

Introduction

Data were collected as described in Chapter 3, using an online survey of staff teaching science. The questions asked are set out in the next section, these are modified versions of those asked to the students based on Holman's (2017) five criteria. Some preliminary questions about accessing the VL and interest in teaching science were included, as a lead into these. The responses to these initial questions are not analysed here, as they do not relate to the current research questions. Two additional questions have been added requiring only a textual response. The Likert and textual responses are then summarised. The results are followed by a brief discussion, which will be expanded in Chapter 5.

Questions

QT1. Do you agree your students learn more about the principles of scientific inquiry from virtual or physical laboratories?

QT2. Do you agree that students gain more understanding of theory through practical experience using real or animations / simulations / virtual laboratories?

QT3. Do you think that virtual laboratories teach students more practical skills, such as measurement and observation, than they learn in a physical laboratory?

QT4. Do you agree that students feel more motivated and engaged using a physical laboratory rather than a virtual laboratory?

QT5. Do you agree that students develop higher level skills and attributes, such as, communication, teamwork and perseverance, when using a virtual laboratory rather than a physical laboratory?

QT6. Do you have an overall impression of how students learn using animations / simulations / virtual laboratories?

QT7. Do you feel animations / simulations / virtual laboratories are a useful addition to teaching and learning? Why do you have this view?

Results

Table 30 shows the Likert data collected in the staff survey. There was an issue with the first question which was found to be ambiguous so only the data for the neutral response is recorded. The data were then simplified to show just positive or negative views of VL. In this case using the textual data it was possible to reconstruct the missing quantitative data, this is shown in Table 31 and Figure 24.

Table 30 showing staff survey data collected in March to July 2023

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
QT1. Inquiry[1]			2		
QT2. Theory	2	1	2	2	1
QT3. Practical skills	1	0	1	5	1
QT4. Motivated	2	4	2	0	0
QT5. Higher skills	2	0	3	1	2

[1] The question, QT1, in this case, was found to be ambiguous so the data were unreliable.

Table 31 showing simplified staff survey data collected from March to July 2023

Question	Positive for VL	Neutral	Negative for VL
QT1. Inquiry [2]	1	2	5
QT2. Theory	3	2	3
QT3. Practical skills	1	1	6
QT4. Motivated	0	2	6
QT5. Higher skills	2	3	3

[2] The data were generated from the written responses which made clear the staff's opinion. One response did not seem to show a preference, and another was blank, these have been recorded as neutral, which agrees with the 2 neutral responses recorded.

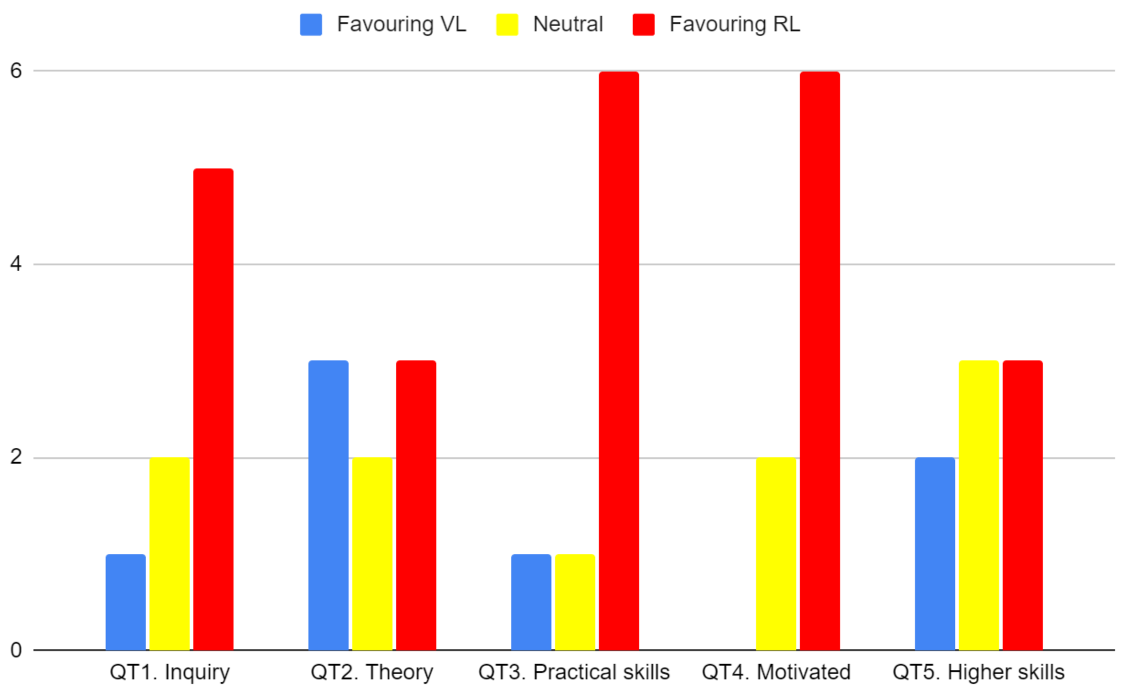

Figure 24 showing simplified staff survey data collected from March to July 2023.

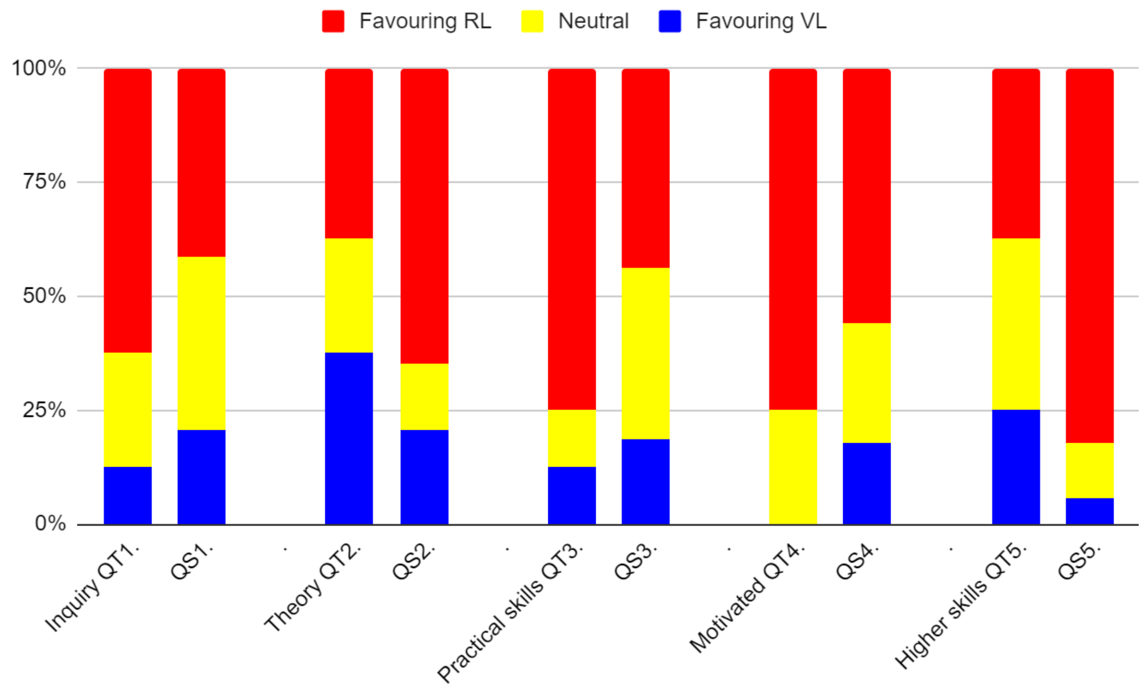

Figure 25 showing a comparison of the response from teachers (QT) to that from students (QS). All data sets have been scaled to allow comparison.

A summary of the textual responses is given here, while the full responses are recorded in Appendix 14. The themes identified are similar to those found in Phases 1 and 2, these are now summarised:

Hands-on: Teachers feel that 'hands on use of equipment re-enforces the theory that the students have learnt' and that in the physical laboratory 'they are in full control – they are the full reason whether a practical will be successful or not'. One teacher feels that 'kinaesthetic learning and fine motor skills are a key element to being a good scientist' and so, 'virtual labs could ever replace the hands-on experience of doing practicals and using the equipment first hand'.

Real world: Teachers believe that their 'student[s] learn a lot of theory through practicals first hand as it allows them to ask meaningful questions and apply the practical to real life scenarios'. For example, when addressing 'the idea that vessels must be placed on a flat surface, that the meniscus may not always be level or clear as a virtual lab would make it', so, 'they need to know how to complete practical tasks in the 'real world' and not one idealized in a computer if they are to get truly competent'.

The physical laboratory involves 'team work and having to be physically involved with the equipment and be an active participant rather than an observer'. This means that 'most students enjoy carrying out practicals physically. [Since] more senses are involved, such as touch and smell'. Additionally, 'many students are stimulated by working together', while in the VL 'clicking mouse buttons can be done as individuals'. Teachers feel that students see the physical laboratory as ''real science' rather than some kin[d] of video game' where 'there are fewer problems in a simulation' so the 'physical lab experiments are more variable, present more and different challenges', giving 'a greater sense of achievement'.

Additional resource: Teachers recognise that 'simulations and virtual labs can allow students to work at home at their own pace and allow more time for understanding. This can be especially true for weaker or neuro-divergent students who cannot grasp new concepts as quickly'. The VL can be 'very useful, esp. for the abstract ideas in science e.g. the movements within cells'. 'They help students visualise, understand and remember concepts and skills. They can make topics more interesting'. However, some teachers feel that 'learners are often not very engaged with them and may not find them very entertaining or useful'. Overall, teachers seemed to find VL 'a good tool to complement physical practicals', 'useful alongside 'real' lab work' and 'good if some equipment is not available'.

Learning tools: Some teachers feel that 'practical experiences ensure students see and think about the theory in different ways which helps their understanding and learning' and that 'learners enjoy the 'real' experience more so they are more likely to remember the content'. Also, the physical laboratory 'engages kinaesthetic learners and uses more parts of the brain including the social areas which could lead to better embedding and long term memory', while working in the VL 'learners have completed the tasks in isolation, so sadly there was zero communication or teamwork'.

However, while students 'learn more in a physical lab with appropriate guidance from the teacher … virtual labs can complement this well with more continuous individual feedback possible than a single teacher with a large class'. Also, a teacher suggested that for students, 'a virtual lab could … be a great tool to use before a practical assessment', which 'enables them to experiment with different situations quickly and safely'.

Discussion

The Likert data from the staff survey shown in Figure 24 showing simplified staff survey data collected from March to July 2023.favour the real laboratory for teaching inquiry and practical skills and providing motivation. Only for teaching theory and possibly higher skills is the VL comparable. Figure 25 showing a comparison of the response from teachers (QT) to that from students (QS). All data sets have been scaled to allow comparison. This shows that the teacher and student responses are similar for similar questions.

The first thing to say about the written responses is that they are much more comprehensive than those by students. Most staff give significant and wide-ranging answers to the questions. The staff use animations, simulations or VL in their teaching to a varying extent and this is reflected in their responses. The textual responses show four themes, however, they are less clear than those for the students. These are 'hands-on'; 'real world'; 'additional resource'; 'learning tools', which largely mirror those identified from students responses and these comments can be related to the research questions. While there is a fairly limited amount relevant to the first two questions there is a significant material towards answering RQ3.

RQ1: There is a general impression that students are more motivated 'students enjoy carrying out praticals physically' and this is different to the VL where 'we have become acclimated to videos' or 'some kin[d] of video game'. While teachers feel that VL is 'useful to show students how to do things before they do them' and that 'they can learn about situations and investigations not possible in a standard lab'. They also believe there is a difference in perception between the 'idealised situations' and 'the idea that vessels must be placed on a flat surface, that the meniscus may not always be level or clear as a virtual lab would make it'. While in a physical laboratory 'more senses are involved, such as touch and smell', than in the VL. 'There are fewer problems in a simulation', while in a 'physical lab experiments are more variable, present more and different challenges'.

RQ2: Students are more likely to trust the results in the physical laboratory 'because they are fully in control of the process. Selecting the correct equipment; interacting with classmates and delegating tasks; seeing the results for yourself and taking ownership of brilliant (or terrible) results and then explaining them'. In the physical laboratory students 'are in full control – they are the full reason whether a practical will be successful or not', so they 'see it a[s] 'real science' rather than some kin[d] of video game'.

RQ3: Generally, staff seem to value VL as an additional resource, which is 'useful to teach theory before or after a practical, as a homework to maybe practice before doing the real thing and as a last resort for virtual learning but can never be a full replacement for learning relevant industry skills'. VL can 'help students visualise, understand and remember concepts and skills. They can make topics more interesting'. It is quite clear, teacher feel, that 'they are a useful addition', 'alongside 'real' lab work', but 'could [n]ever replace the hands-on experience of doing praticals and using the equipment first hand'.

Staff identified several positives, as 'a virtual lab could always be a great tool to use before a practical assessment' as 'an additional tool to help explain how to carry out a practical'. So, they are 'useful to show students how to do things before they do them'. The VL can also provide scaffolding and a safe space, which is 'especially beneficial to learners who feel initially anxious about physical practicals'. 'This can be especially true for weaker or neuro-divergent students who cannot grasp new concepts as quickly'. Teachers also highlight that, for students' learning, a VL 'enables them to experiment with different situations quickly and safely'. 'They are a good tool to complement physical practicals' as students can 'recap key skills' and are 'useful 'especially when re-enforcing the theory that the students have learned'. VL can be 'very useful, esp. for the abstract ideas in science e.g. the movements within cells', meaning 'that students' learning is better with them'.

There are also some practical advantages, as VL can provide 'more continuous individual feedback possible than a single teacher with a large class'. While students 'can learn about situations and investigations not possible in a standard lab'. Additionally, VL are 'good if some equipment is not available' 'and save on resources'.

So, overall, we have a tentative answer to RQ3: - that teachers have confidence in the educational value of learning in virtual laboratory as an additional learning tool, but not as a replacement for the physical laboratory. This will be explored further in Chapter 5.

Phase 4 data

Introduction

The data presented in this section are the result of two interviews with teachers in June and July 2023. The interviews were recorded, transcribed and checked, in the same way as the student interviews (see above) and as described in Chapter 3.

The themes identified in the data were similar to those seen for the student data (above), so for consistency I am also using those to classify the teacher interview data. In the same way as before, I have set up tables for each of my themes and the three research questions, then copied relevant parts of each interview into the tables.

The next section gives some more specific information about the interviews, building on the information supplied in Chapter 3. This is followed by the results of the thematic analysis, which are presented separately for each theme and research question. As before I have followed Connelly and Clandinin (1990) in trying to allow the teachers space for 'telling their stories in words as they reflect upon life and explain themselves to others'.

Interviews

The teacher interviews were carried out as described in Chapter 3. As a practitioner researcher and a colleague of the teachers interviewed, the interviews were at some points conversations of shared experience, rather than interviews. This has the advantage that the teachers were more open with me than they would be with an external researcher, but as I am part of this conversation, I may also influence their responses. So that others can judge how much I affected the conversation, I am deliberately including some of the questions and comments I made during the interviews. In reporting the interviews, I have distinguished the *spoken words* of the staff and myself as interviewer by using *italics*, rather than inverted commas, which can become cumbersome.

Thematic Analysis

This section is divided, as for the student interviews above, by theme and each is considered separately. The results relevant to each of the research questions are then reported. Again, I have attempted to provide a 'thick description' (Lincoln and Guba, 1985, p. 316; Nowell et al., 2017), though extended extracts given in Appendices 15-18; these allow the reader to better judge the transferability of the conclusions.

The themes which were identified from the student interviews, are also largely found in this data, these are: **Hands-on / reality; Doing it myself / control; Method / skills; Theory / knowledge; Trust / truth**. These are described in the Phase 2 section, above.

T1. Hands-on / reality

The extended extracts from the teachers' interviews are presented in Appendix 15 and these are discussed in more detail here.

For Teacher S the VL is a tool which can show the learners what the real experiment will be like – *'it is a mirror of what we do in the lab. I've always pitched it like that, and I think they do see it that way … it is representing what we do in the lab, and I think they have no trouble with that concept as far as I'm aware'*. However, VL does not provide all the experiences and hands on interactions that students have in the real laboratory. The real laboratory is a busy place where it *'often it takes two or three people … working simultaneously'*. There is also the physicality of touch and feeling *'the different textures of the … things you're dissecting for, the different way you're gonna feel when you're dissecting something ... a lot of my students faint when they do it. So … there's emotions attached to it and that helps with learning … and forming those long-term memories'*.

Teacher S also suggests that students value being part of something which is actually happening, where *'there's just more inputs … different kinds of stimuli hitting you at once ... Instead of just visual information and auditory information, you are also having to sort of feel things, having to think about things, having to talk as well as do the practical'*. This gives the students a richer experience, *'they can see that they're collecting … real data and I think they appreciate that because then we can have really interesting discussions about like, why was that data not perfect … what variables can we not control in biology … why do we have to do a mean, because there's so many different … things that could be affecting the results today'*. This translates into a more fundamental insight – *'I think, they see that biology is real and tangible … through the sometimes untrustworthiness of the results, you can get a real sense of how to use it'*. This also provides the teacher with a motivation, feeling *'that's why I really find wildly exciting because sometimes you just get unexpected results'*. The teacher too, feels linked into the world where '*the results are never quite what you expect'*, rather than the VL where *'the results are finite and set, pre-set'* and so predictable.

Teacher T talks about the physical experience of quantitative observation in judging '*the meniscus, whether it's 0.05, 0.00, I think you could get that kind of skill and knowing, … what are the numbers I need to record here, I think you could get that from [either laboratory]'*. However, there are more qualitative observations, such as *'the difficulties of judging an end point would be far better done … with a real colour change, because there's no idea how they do colour change shades on in the virtual world … what is one person's burnt orange is another person's completely red. So, I think they would get some practical element, useful practical skills … but some of the more qualitative ideas about colour changes would be better in reality'*.

There is also a second thread, this is the link to what might be called mundane physical activities, rooting students in the present. There is *'something happening in front of them … [students are] splitting of duties, washing up, cleaning up, getting things out is, has to be done physically'*. For many students they *'like being around people, they like talking to people, they like interacting with them; and the physical, practical work allows all of that'*. While Teacher S suggests *'if you had to do that practical again … you'd be far more likely to do better, having done it once before; than having learned about it virtually and just looked at the theory of it. You sort of made that muscle memory almost'*.

A third area which can make the physical experience more real and engaging is *'the social aspects, where you need to be, what you need to do at each moment, and how that actually all works together'*. While Teacher T believes *'it instils … camaraderie and I think the students, that I have, going into health professions … enjoy that and enjoy working with each other'*.

T2. Doing it myself / Control

Extended extracts from the interviews on these themes are given in Appendix 16. These suggest the importance of agency, authorship and authenticity. This is expressed by ***TEACHER S:*** '*I think [the students gain more working in the real laboratory] because they're doing it themselves, they know … what equipment they're using and they have autonomy over the results they're getting. I think … they feel like they can trust the results because they're the ones who created their own'.* The students are able to make choices '*in a real lab, something's gone wrong, something's not working – they have to figure it out. They have to figure out which equipment piece needs replacing or fixing or cleaning and … sometimes it doesn't work. So, they have to go back and think, right, okay, this time I'm gonna try a slightly different concentration.'*

Sometimes students feel that their own results are more authentic, for example ***– TEACHER S:*** *… sometimes when I give them … data from an exam question, they're like, oh, but we didn't quite get that in our results … they're always like referring back to their own results and I think they sometimes trust those more because they saw it happen with their own eyes instead of just like, numbers on a piece of paper. And I'm like … this is more like what you're supposed to get and they're like, yeah, but we got this, and I think … they tend to trust their own results sometimes a bit more.*

T3. Method / Skills

In general, the teachers seem to value the skills gained in the real laboratory, this is shown in the data recorded in Appendix 17. While neither teacher has extensive experience in using VL, but both can see the potential value of it for learning.

Exploring first their thoughts on the real laboratory, we find what is important for ***TEACHER S:*** *… doing the [real] practical, not just … the fiddly things that you're doing with the equipment, but also the social skills you need to, to be able to use equipment … the social aspects, where you need to be, what you need to do at each moment, and how that actually all works together … encompasses so many more different social elements to it, as well as fine tuning the fine motor skills you need for a lot of different [praticals]… like some of the dissection practicals… the different textures … the different way you're gonna feel when you're dissecting something like [a heart]* ***…*** *Different kinds of stimuli hitting you at once … Instead of just visual information and auditory information, you are also having to sort of feel things, having to think about things, having to talk as well as do the practical. So, it's multitasking skills as well … they're developing skills for life … there's so many different elements to your practical, it's not just the theory of doing it, it's not just the step-by-step plan, it's … I think a lot of the practical skills you learn physically are, so I say it, they're far more useful for the future* ***…*** *we do a lot of microscopy skills, and a lot of biology jobs involve a lot of microscopy, so that's something that's quite transferable.… if you had to do that practical again … you'd be far more likely to do better, having done it once before; than having learned about it virtually and just looked at the theory of it. You sort of made that muscle memory almost.* From this we can draw out value placed on social, teamwork and motor skills; which this teacher feels will not be developed so effectively in the VL. This is also felt by ***TEACHER T:*** *… in the practical world … the skills … include the … splitting of duties, washing up, cleaning up, getting things out it has to be done physically … I think teamwork certainly comes into it and, you know, cleaning up at the end and getting things ready is part of teamwork … [Students on] health related courses … like being around people, they like talking to people, they like interacting with them; and the physical, practical work allows all of that … it instils … camaraderie...*

Similarly, ***TEACHER S:*** *Teamwork's definitely one that's developed better in a real laboratory rather than a virtual lab … perseverance, that's definitely needed in some of my … biology practicals; but with the virtual lab, everything works instantly. … there's no, you know, having to problem solve, particularly … go work through the steps; whereas in a real lab, something's gone wrong, something's not working they have to figure it out. They have to figure out which equipment piece needs replacing or fixing or cleaning and then yeah, sometimes it doesn't work. So, they have to go back and think, right, okay, this time I'm gonna try a slightly different concentration … on the spot, problem solving and quick thinking and teamwork and communication, it all comes together into one cohesive learning experience. That's really valuable.*

The teachers also see some practical skills as difficult to develop in the VL. ***TEACHER T:*** *… the difficulties of judging an end point, would be far better… with a real colour change … what is one person's burnt orange is another person's completely red. So, I think … the more qualitative ideas … would be better in reality.* While, for ***TEACHER S:*** *…I just don't think it would work as well, and it won't prepare you for the different textures of the things you're dissecting.*

However, for some simple skills such as measurement, ***TEACHER T: …*** *whether it's 0. 05, 0. 00, I think you could get that kind of skill and knowing; right – what are the numbers I need to record here. I think you could get that from [VL].* While there are other skills developed in the VL. Asked –

INTERVIEWER: *Do you think students gain skills from the VL?*

TEACHER S: *… communication if they're reading and having to interpret information, and if there's follow up questions in the virtual lab … [they are] developing their understanding and reasoning. But I think there's far more higher order skills that are developed through doing a real practical. … evaluation, you can do virtually that …they can evaluate improvements for a practical … in theory as well as in practice. So that's a high order skill that they can do ... … you are usually doing that alone …*

Moreover, for ***TEACHER T:*** *… higher-level skills … abstract concepts … I think any would be fine for it. I don't think that a practical laboratory would necessarily benefit you … consistently for those high-level skills of evaluating – why an experiment worked well, why it didn't, why you were getting a low yield, a higher yield.* With an advantage that VL can provide *… abstraction – I think it is that; at the minute we can use virtual laboratories, we can see things that we couldn't see before… we are moving on with that kind of abstract ideas. Development and seeing them in action … but … I don't think … there's a benefit of one over the other.*

For some skills the VL has an advantage, ***TEACHER S: …*** *[the students] manipulate a molecule using a program or an online resource… PAG 10 is … virtual, I don't think it's a virtual lab, but …[students] manipulate molecules on the computer program and like measure things … on the DNA molecule. So, some of the things we do are using … computer modelling, so that is gonna prepare them for … industry in the future ... I think all of our praticals do prepare for no … matter what industry [they] go into …*

T4. Theory / Knowledge

The teachers also see a place for VL as a vehicle for transmitting theory as part of the learning activity.

INTERVIEWER: *… do you think students gain more understanding of theory through practical experience using real or animations, virtual laboratories?*

TEACHER S: *I think doing the praticals help with their memory of how to do the practical, the method. However, like I'm just thinking about the, the polymerase chain reaction … as you go through each step, it explains what's happening at each step, and that's something you might not necessarily get, when doing the practical, like they might remember doing the practical, but they might not remember me explaining things before and after and as we go through, because I'm always just standing at the front talking to them. So, actually some of the virtual labs, especially for the biotechnology bits and bioengineering is quite good because they can take their time with it, write notes down and one of 'em has like little multiple-choice questions at the end … for a bit of assessment for learning. So, I think for theory actually, some virtual labs are quite engaging.*

TEACHER T: *… Do I think they gain more... understanding of the theory? … I think it's possibly more memorable, but whether that's, that's not necessarily understanding, is it? Understanding is something more intricate. I don't know is the truthful answer … about the true understanding, because I think they could gain … an understanding from any of them; in as much as they will gain an understanding …You could teach someone to do a titration and … get the correct figures, get the end point, put the numbers into a calculation, but actually understanding what's happening, why does it need to be multiplied by two, divided by two? Why does it react like that – I'm not sure.* So, we can see that Teacher T has some more fundamental questions about the nature of learning and understanding: such questions are discussed in Chapters 2, 3 and 5.

T5. Trust / Truth

The interviews with teachers also generated data concerning trust, this data is given in Appendix 18. Three issues emerge, the trust of students in their teachers, the trust of students in computers and the trust of the teachers in the results of real and VL experiments.

Students trust in teachers

Teachers believe that students trust them, for example when they give their students a task – ***TEACHER T:*** *I think that's because they would trust me, to not allow them … to go down on a wild goose chase. … go off on a tangent and get ridiculous results. I think they would think, well – know, the lesson will have been sculpted in some way to not allow that and the practical work would reflect that … that's my perception … of my type of student.* Specifically, in the case of VL, ***TEACHER T:*** *… I think they would imagine, well, [(the teacher's own name) is] gonna have doctored it. He's not gonna give us a program that would just give us nonsense results, irrelevant results. I think they would believe that the results they get … from the computer would've been in some way doctored to be closer to the [right value], I think that anyway.*

This illustrates the complex relationship between teacher and student. The teacher believes the students will trust him to give them something of value and in the teacher's response there is an acknowledgement of that trust. This point is further illustrated by Teacher S who describes how they deal with using a practical analogy in their teaching.

***TEACHER S:** … Well, they know sometimes some of my … mock-ups ... I just tell them the truth. I'm like, this is a model, this is not real life – I'm not using the actual enzyme – Just pretending. But I think because they see how the results are different each time and how … the results are never quite what you expect. They can see that they're collecting … real data.*

There is a value placed on honesty in this situation, which Teacher S uses to demonstrate '… *that biology is real and tangible … through the … sometimes untrustworthiness of the results'.* In a sense Teacher S is asking the students believe to their story, about something which is not real, but tells them something about reality. This is a similar case for VL, for which ***TEACHER S:** … [is] confident that [VL] explains things correctly, but at the same time, I do always just double check … I've not really found any that are wrong …* In this case Teacher S, feels they need to provide some sort of *… 'quality assurance test'* so that they are *'confident in … that information is correct … and check them just to make sure they're right for OCR'.* This relates to the teachers trust in VL which is discussed below.

However, students trust in their teacher is not entirely blind. ***TEACHER S:** … sometimes when I give them … data from an exam question, they're like, oh, but we didn't quite get that in our results … they're always like referring back to their own results and I think they sometimes trust those more because they saw it happen with their own eyes instead of just like, numbers on a piece of paper. And I'm like … this is more like what you're supposed to get and they're like, yeah, but we got this, and I think … they tend to trust their own results sometimes a bit more.*

***INTERVIEWER:** … even though you tell them, okay, this is what you should have got*

***TEACHER S:** there's always still the pushback. Yeah, but we got this … I suppose that sparks debate, but I think they do get that in science … this is the set data and what we get will always slightly differ, cause that's just the way it is.*

This is also brought out by ***TEACHER T:** … my experience of doing the physical practical is you will get some students, some groups who get ridiculous results. …. It's a bit of fun, when that happens, but … they would at least trust them and say, well, something went wrong, something actually went wrong, we did something wrong, and we can investigate what that was, of course … they do trust them in as much as, well, they were the real results we got, even if they were completely different to everyone else's in the class. Whereas, if that was in a virtual environment, I think they would suspect well, that was probably done on purpose to give that outlier to provoke some debate rather than it just happening because they had done something wrong.*

Here Teacher T feels that students would trust their own results in the sense of causality '*the real results we got'*– the result of a series of actions; but would trust the teacher to say, '*something went wrong'* and these are *'ridiculous results'.* There appears to be a separation of belief in theory and practice – received knowledge and experience.

Students trust in computers

Teachers recognise that their students tend to believe the outputs from computers. ***TEACHER S:** … I think … young people especially have a tendency to just believe things they see on the internet … So, I think the students probably regard the … virtual labs as kind of like a best-case scenario result – Not very realistic, but still fairly reliable, if that makes sense.* So, students have an inherent faith in the computer, they would rely on the result, but may feel the experience is not authentic. This theme is also reflected by, ***TEACHER T:** if I said to them, you're gonna do two practicals, you're gonna do one in class, you're gonna do one via a computer, which do you think … would give you the closest results to the true value? They probably say the computer, but if I asked them why, they would say … because it's a computer … it's gonna tell me the right answer. … but if I said … which ones, do you think people* *are, if they do the experiment themselves … more likely to get? … not necessarily the accurate ones nearest the value – what are they more likely to get? I think they would pick the … in-class practical work. … I think they would believe that the results they get … from the computer would've been in some way doctored to be closer to the [right value] ….*

Teachers trust in experiments / VL

The teachers appear to believe in the accepted theory in preference to the evidence of their students experiments. An example is described by:

TEACHER S: *… a huge, like ridiculous conflict? … we have had that actually before … we did have an experiment that just went totally wrong, and we got the complete opposite relationships and what we shouldn't be seeing. And I can't help thinking that either … the technician or some something went wrong somewhere in the dilution, and either were [mis-] labelled maybe, and that could have been why it went wrong … at the end of the experiment I was like, well, that didn't quite work how we planned … what could that have been?* Here the teacher is expressing a belief in the theory, accepted knowledge and paradigm – there is a 'right answer', and the experiment has failed to demonstrate it, so we ask why?

TEACHER S: *… Why do you think that happened? Again, promoting good discussion. That's something you don't get in a virtual lab … just trying to figure out what went wrong and improve the next time … they learn that they always have to evaluate, think back, and then repeat the experiments to try and get the correct results in the future'.*

The focus is on the 'correct results', however, for the teacher who is also a scientist, they question: *'… in science you sometimes you find something new, don't you? … if something's not following the pattern, you might repeat it and see if it happens again, and then think, okay, now I discover[ed] something new'.* Also '*because sometimes you just get unexpected results and then you have to have fun trying to explain it';* it adds to the teaching and learning experience.

Furthermore, ***TEACHER S: …*** *I think because they're doing it themselves, they know … what equipment they're using, and they have autonomy over the results they're getting. I think … they feel like they can trust the results because they're the ones who created their own space in the first place'.* This teacher feels that the students level of trust in their results is increased by their engagement in the process of generating them.

When it comes to the VL teachers (and students) feel more distant from the process of generating results, ***TEACHER S:*** *… I'm never really sure in some of these labs, the virtual labs, if the results are finite and set, pre-set, or if they use like a random number generator or something. It'd be probably more realistic if they use the random number generator because sometimes the numbers we get are just … within like set limits, but that would be quite useful cuz it kind of mirrors more like what you're gonna get in real life and that's why you do a mean, but I think sometimes they just use set numbers, you know, like you will get 2%, 4%, 6%, and it doesn't always work that way. So, I think the students probably regard the … virtual labs as kind of like a best-case scenario results – Not very realistic, but still fairly reliable, if that makes sense.*

Teachers do express a trust in the VL but that is in part vicarious. Asked about their level of trust in VL, ***TEACHER S:*** *… I'd say quite a lot, because most of them are made by … sort of quite reputable universities or companies. … I trust … that they have done their research and they've got everything right, as you always sort of check through them though, is that not being trustworthy then?*

Because I always do check through them, so maybe I don't have a hundred percent, but … 99% sure that, I'm confident in what, that information is correct, but I do like to go through and check them just to make sure they're right for OCR … I'd say … pretty confident.

INTERVIEWER: *… that shows trustworthiness in the sense that you've gone through a process which assures you …*

TEACHER S: *… quality assurance test … I'm confident that [it] explains things correctly, but at the same time, I do always just double check … I've not really found any that are wrong …* So, this teacher wants to also check the VL and seems to use the OCR specification as their guide.

T6. Risk/Consequence

This is an area which did not really feature in the discussions with the teachers. Perhaps this is because teachers have confidence in their risk assessments and the safety of the practicals. While also feeling that if an experiment *'didn't quite work how we planned … we came up with some ideas about why it didn't work and so I think …they learn that they always have to evaluate, think back, and then repeat the experiments to try and get… the correct results in the future'* (Teacher S); so, it could be turned into a learning experience.

RQ1: The extent to which students experience learning in a virtual laboratory as a mirror of reality?

In this section, the data has been reanalysed to focus on answering the specific research questions. The aim is to bring together the material which is directly relevant to RQ1. There will inevitably be some overlap with the thematic analysis above, but I have tried to minimise this.

TEACHER S: *… I think … they see things in real life, and they see that … it is a mirror of what we do in the lab. I've always pitched it like that, and I think they do see it that way. Like … we went to Hallam and we did polymerase chain reaction … set it up and then we did a virtual lab on it and they were like, oh yeah, like in Hallam, you know, like they can see that it is representing what we do in the lab and I think they have no trouble with that concept as far as I'm aware.*

TEACHER T: *… I think they found it a good mirror in terms of what's happening at a molecular level to the bonds and what's happening inside the machine. I think they found that a very good mirror, but not in terms of them producing, doing the practical themselves – I don't know that ... but a good mirror as to … actually what's happening inside there.*

There are aspects where the mirror is not as clear; with a physical mirror we can see reflected light and hear the reflected sound of an echo – these can be provided by the VL. However, in the VL used by these students they cannot experience many of the aspects which make up the physical practical**,**
TEACHER S: *… they're also developing so many skills that you need for doing the practical … encompasses so many more different social elements to it, as well as fine tuning the fine motor skills you need for a lot of different practicals; like some of the dissection practicals – there's no way you'd be able to learn that online. And then someone says … go and dissect a heart using your knowledge from all that you've learned online – I just don't think it would work as well, and it won't prepare you for the different textures of the things you're dissecting for the different way you're gonna feel when you're dissecting something like that. I mean, a lot of my students faint when they do it …, there's emotions attached to it and that helps with learning … I don't think it compares. Sorry.*

TEACHER T: *… I think the difficulties of judging an end point would be far better done in class … with a real colour change, because there's no idea how they do colour changes [or] shades on in the virtual world, but … looking at it in reality what is one person's burnt orange is another person's completely red.*

Discussion

So, for these teachers the VL is a good mirror tool for some aspects, providing a meaningful contribution, but for others it does not provide a useful reflection. Specifically, the teachers view those aspects of reality which relate to theory or abstract concepts as being equally well dealt with in the real and VL, *'especially for the more abstract concepts like … teaching infrared spectroscopy'.* So, for these cases students *'will be able to learn equally as much … in a virtual laboratory'.* In a sense the teachers are saying that students are still *'developing their higher order skills'* in the VL, this part of the experience is the same. However, there are other areas such as '*social elements … as well as fine tuning the fine motor skills'* which are only really present in the real laboratory.

RQ2: The extent to which students regard the results of experiments conducted in these environments as trustworthy?

In this section, the data has been reanalysed to focus on answering RQ2. The material covers the students trust in both types of laboratory, focusing first on the VL.

INTERVIEWER: *… to what extent do students regard the experiments conducted as trustworthy?*

TEACHER S: *… in the virtual lab? I think … young people especially have a tendency to just believe things they see on the internet and I'm never really sure in some of these labs, The virtual labs, if the results are finite and set pre-set, or if they use like a random number generator or something it'd be probably more realistic …. So, I think the students probably regard the… virtual labs as kind of like a best-case scenario result. Not very realistic but still fairly reliable, if that makes sense.*

… most of them are made by, you know, sort of quite reputable universities or companies … I trust that they have done their research and they've got everything right. As you always sort of check through them though, is that not being trustworthy then? Because I always do check through them, so maybe I don't have a hundred percent [confidence], but … 99% sure … I'm confident … that information is correct, but I do like to go through and check them just to make sure they're right for OCR. I'd say … pretty confident. I'm confident that [the VL] explain[s] things correctly, but at the same time, I do always just double check … I've not really found any that are wrong …

TEACHER T: *… if I said to them, you're gonna do two practicals, you're gonna do one in class, you're gonna do one, via a computer, which do you think would give you … the closest results to the true value? They probably say the computer, but if I asked them why, they would say, well, because it's a computer isn't, it's gonna tell me the right answer … but I, if I said to you … if they do the experiment themselves, what are they more likely to get? … not necessarily the accurate ones nearest the value – what are they more likely to get – I think they would pick the … in-class practical work.*

INTERVIEWER: *Why do you think they would trust the computer?*

TEACHER T: *… I think they would imagine, well, [(teacher's name) is] gonna have doctored it. He's not gonna give us a program that would just give us … nonsense results, irrelevant results. I think they would believe … that the results they get … from the computer would've been in some way doctored to be closer to the, I think that anyway.*

INTERVIEWER: *And you think that's because they would trust you?*

TEACHER T: *I think that's because they would trust me, to not … [to] allow them to go down on a, on a wild goose chase … go off on a tangent and get ridiculous results. I think they would think … the lesson will have been sculpted in some way to not allow that, and the practical work would reflect that.*

Students do have a belief in what they actually see in the real laboratory***, TEACHER S:*** *… I think because they're doing it themselves, they know … what equipment they're using, and they have autonomy over the results they're getting. I think they feel like they can trust the results because they're the ones who created [them] in the first place … they're always … referring back to their own results and I think they sometimes trust those more because they saw it happen with their own eyes instead of just … numbers on a piece of paper … they tend to trust their own results sometimes a bit more.*

However, there are times when things are not all they seem, for ***TEACHER S:*** *… sometimes some of my … mock-ups … I just tell them the truth … this is a model. This is not real life. I'm not using the actual enzyme. Just pretending … but I think because they see how the results are different each time and* *how … the results are never quite what you expect. They can see that they're collecting … real data. And I think they appreciate that because then we can have really interesting discussions about like, why was that data not perfect … what variables can we not control in biology … things that could be affecting the results today … they see that biology is real and tangible … Through the … sometimes untrustworthiness of the results, you can get a real sense …*

***…** we did have an experiment that just went totally wrong, and we got the complete opposite relationships and what we shouldn't be seeing … some something went wrong somewhere … in the dilution, and either were [mis]labelled maybe … at the end of the experiment I was like, well, that didn't quite work how we planned.*

Discussion

There appear to be two distinct paradigms that students work in. One is the real laboratory this is based on experience, physical interaction, control of the situation. The paradigm for the VL is different it is based on trust – trust that the teacher and VL provider are knowledgeable and trustworthy, this is the trust we put in experts and textbooks, not a trust in self. In this sense VL is not practical, but theoretical in nature. *…. So, I think the students probably regard the… virtual labs as kind of like a best-case scenario result. Not very realistic but still fairly reliable*

RQ3: The extent to which teachers can have confidence in the educational value of learning in the virtual laboratory?

Teachers are not a homogenous group and so the opinions of just two of them cannot be considered representative. However, by listening to their views it is possible to gain a flavour of teaching science in FE. The teachers interviewed might be considered to be 'mid-career' and so have some years of teaching experience. The views of the teachers about VLs seem to be mainly focused on their role as a support or addition to real practical science.

So, for ***TEACHER S:*** *doing the practicals help with their memory of how to do the practical – the method'*. The VL can help with this, for example the VL helps, *'as you go through each step, it explains what's happening at each step, and that's something you might not necessarily get when doing the practical … they might remember doing the practical, but they might not remember me explaining things before and after, and as we go through, because I'm always just standing at the front talking to them. So, actually some of the virtual labs, especially for the biotechnology bits and bioengineering is quite good because they can take their time with it, write notes down and one of 'em has like little multiple-choice questions at the end … for a bit of assessment for learning … I think for theory actually, some virtual labs are quite engaging.*

The VL can also help support the assessment for learning, when (***TEACHER S)*** *… you're trying to assess things or make sure that a learner has described this, explained that, evaluated this … carried out that practical, it can be difficult sometimes to be sure that every single student has met every part of that practical, like were they actually helping the whole time … have they managed to understand the point of the practical or did they just follow the instructions? … it can be difficult to measure that, I suppose, in an environment that can be confusing and there's lots going on and there's people pulling you here, there and everywhere. So, yeah, from a teaching perspective, I think while practicals are fun, engaging, it may not be the best way to assess for learning, … you can't be sure that students are meeting targets that whole lesson, especially if things go wrong, whereas in a virtual lab … you know … if they've been engaged the whole time, have read the information, have hopefully understood the information … if* *they don't, they can go back and look at the information a second time … I suppose using a virtual lab is more, is more measurable in terms of how well they've … accessed that information. Whereas in a classroom when there's a lab … experiment going on, there could be students that fall through the cracks and don't fully understand what's happening and they just sort of do it and then it's over and they're not really sure what happened. I feel like that must happen often. Actually, you know, one or two students are just sat in the corner not really totally getting it. That happens a lot in microscopy, if they could make a virtual lab for doing the microscope measurements, that'd be really useful.*

Modelling is an important part of teaching science; most theories can be expressed as models which in some way bridge the gap between the abstract and the concrete. Teacher S, talks about teaching through modelling, in the real world: … *with so many things in biology, it's a process. So, it's really useful to then show it visually … if that still doesn't work, then we'll go on and … model it maybe with Plasticine or something like that so they can really get their hands on it and figure it out. Do all the moving parts … so you're getting lots of differentiation from sort of [thing]; hearing about it, seeing it work on the video, and then doing something a bit more kinaesthetic is really good for engaging all different types of learners … they can model pretty much anything … really good for the sort of unseen biology, like the biochemistry … respiration and photosynthesis. … It's really good for membranes.*

So, we might wonder if this has been extended to virtual laboratories. There is an example given by ***TEACHER S:*** *… I use [a VL] for potometers as a bit of a homework preparation before they do the practical so they can play around with it and hopefully understand the apparatus before then coming in to do the lesson. Just saves a lot of time and then they know it: and I used a few more … during lockdown, during Covid.* However, there seems to have been only limited use of VL, in day-to-day teaching. It is not that VL is not considered as potentially useful. ***TEACHER T,*** considers the possibility *… of flipped learning where you might say this is what we're gonna do next week – Just have a go at it … just have a look at these Instructions, see what you have to do. You can move things about, you know, move the pipette, fill the pipette up, that sort of thing. How do you do it? Yes, I think it would be a great introduction to it.*

Asking specifically about ***(INTERVIEWER)*** *… how much confidence do you have in the educational value of virtual laboratories?*

TEACHER S: *I'd say, I'd say quite a lot … I'm confident that [they] explain things correctly. But at the same time, I do always just double check.*

INTERVIEWER: *… Have you come across any that, where you where you think, no, this is … wrong …*

TEACHER S: *not yet … in my search for … different ones, like the potometer one, I did find a couple that were kind of clunky, but slow or just not very engaging, you know, a bit boring … I prefer ones that are quite quick, and the student can move through at their own pace...*

INTERVIEWER: *… do you have an overall impression of how students learn using animation simulation, virtual laboratories – so how they're learning?*

TEACHER S: *Well, they're learning visually, they have auditory sometimes as well. It can be kinaesthetic, … you have to move with your mouse things and put it in that tube; there is some evaluating as well. So, they're developing their higher order skills and there could be a little bit of communication … because they are taking in information and reinterpreting it into some questions and answers. They're also learning alone a lot of the time, so it's independent learning; which is good, good skill for university.*

INTERVIEWER: *What about the quality of the learning in the virtual laboratories?*

TEACHER S: *… It depends on the learner. I think some learners, really good independent learners could go away, use all that information, write it down into neat notes, and then learn from it. Other students click through, yeah, I kind of get it and then never think about it again. So, I think, it's a good tool, but it depends how the student uses it; that's something we can model in class so that … [we] learn how to … make the best of those resources. But I think especially if they're working independently, there's always gonna be the student that does the bare minimum and doesn't actually take on the information correctly. So, I think they're not universal, but if used correctly, they can have pretty good learning outcomes.*

TEACHER T: *I haven't used virtual laboratories, no. I must admit to that … [However,] we certainly use board works and animations. Especially for the more abstract concepts like … teaching infrared spectroscopy. We don't have an IR in the building, of course, so these things are a bit more abstract. … And you say, well, this is happening, this is what the machine looks like … seeing a molecule with an imaginary bond … it looks a bit like a spring and they can just choose different wavelengths and nothing happens for some, but then it does for some of the others and they get the idea of it … and link that with the dip in the IR [spectrum]. So, I've certainly used it for things like that, which is jolly useful because we just, [do not have] those instruments … They have to know that linked with … drug testing, especially … for drink driving and it's useful to … spot the CH bond ... Otherwise, it's just a very abstract, here's a machine, put it in, press the button and it brings this reading out and the reading doesn't mean anything. It's just something they have to interpret very abstractedly, but knowing … that dip is because this bond was doing that ... I think makes a more useful teaching aid.*

INTERVIEWER: … *do you think that students learn more about the principles of scientific inquiry in a virtual or a physical laboratory?*

TEACHER T: *… I am going to show my old-fashioned nature answer and say a physical laboratory. I think if you'd asked me this 20 years ago, I would have perhaps said, oh, but they because it was novel at that point. I think we're becoming more saturated with virtual reality will be able to learn equally as much and they'll enjoy it more in a virtual laboratory – doing things online. So, I think the … pendulum is beginning to swing back a little bit to doing things in the lab and actually getting hold of them. I think there's a place for virtual laboratories. I think it's useful in the beginning and then … so you might do this and then put it into practice physically. I don't think that the physical practicality of science can ever or ought to be ever removed. I think … that virtual learning, especially as a reinforcement, … you might do that first and then the proper practical, but again you could do it after the practical as well as a reminder, … certainly has a place.*

… alongside traditional in college, in class teaching … I do have confidence in their ability to add, to teaching practice, to learning … the type of learning it provides is of course, independent and any time, and we are sort of moving after coronavirus – to that. Well, can we study at any time … When does the learning have to take place? Does it have to be fixed? Well, Monday to Wednesday at these times; whereas the virtual labs will add to that, and students can do it at their convenience and there is a move towards that … I do think they can add to it, especially the busy lives of our adult students.

… *I think it's a useful – additive. I think it's a useful different way. I think … if you can use as many different ways as possible to try and produce, invoke learning … another weapon in the armoury …, and some will like it, some won't, but that's the idea of teaching. We don't just do one, single thing all the time. It is varied and some people will like this … some people will like that. You cannot please everyone all the time, but you can please some people some of the time … I think teaching … an imperfect a procedure – of course it is. There's no such thing as a perfect lesson; a perfect teacher; a* *perfect student … as long as we can employ some methods that work for some people, some of the time in a very high degree and in the others … in some degree I don't think you're doing too badly and … I certainly think virtual labs would add to that.*

Discussion

Although teachers have limited experience of using VL in their teaching, they see its value as an extension of class practicals. Teachers seem to believe in the educational value of practical activities. Specifically, they identify them as '*fun, engaging', 'it instils … camaraderie',* helping with *'social skills'* and *'memory'.* It also *'teaches them far more practical skills … there's so many different elements to your practical, it's not just the theory of doing it, it's not just the step-by-step plan, it's … the social aspects, where you 'need to be, what you need to do at each moment, and how that actually all works together'.* They see the practical as more than learning science *'it's multitasking skills as well; all of which are gonna be useful in later life – it's not just developing skills in science. They're developing skills for life and they're gonna have to work with … problems and people their whole lives'.*

There are some activities which teachers focus on as 'core' activities, for example dissection and titration. The VL can contribute to the theory and method for these, but not the hands-on and social skills which teachers also wish to develop alongside the curriculum. In some cases, '*they will be able to learn equally as much … add, to teaching practice, to learning …, independent and any time … the virtual labs will add to that, and students can do it at their convenience and there is a move towards that … especially the busy lives of our adult students'.* There is educational value in diverse methods – '*additive … another weapon in the armoury … some will like it, some won't, but that's the idea of teaching. We don't just do one, single thing all the time. … You cannot please everyone all the time, but you can please some people some of the time …an imperfect a procedure … as long as we can employ some methods that work for some people, some of the time … I don't think you're doing too badly and … I certainly think virtual labs would add to that.'* So VL has a value as part of the educational mix but for some things '*– there's no way you'd be able to learn that online'.*

Image analysis

The RSC titration screen experiments are one form of VL, the Level 1 titration activity, has been analysed through the lens of Gestalt theory. Appendix 19 shows that these principles are applicable and are important in the overall experience for the students.

Summary

The data for Phase 1 of the study for student survey responses are summarised in Table 32 and Table 33 and those for interview responses from Phase 2 in Table 34. The data from teacher survey responses from Phase 3 are summarised in Table 35 and Table 36, while that from the interviews in Phase 4 are given in Table 37.

Table 32 showing a summary of the Likert results for Phase 1

Survey questions for students	Percentage favouring VL / %
QS1. Thinking about you experiences with animations / simulations / virtual laboratories; do you learn more about the principles of scientific inquiry from these than from physical laboratories.	21
QS2. I gain more of an understanding of theory through practical experience using real rather than animations / simulations / virtual laboratories.	21
QS3. Virtual laboratories teach me more practical skills, such as measurement and observation, than I learn in a physical laboratory.	18
QS4. I feel more motivated and engaged using a physical laboratory rather than a virtual laboratory.	18
QS5. I develop higher level skills and attributes, such as, communication, teamwork and perseverance; when using a virtual laboratory rather than a physical laboratory.	6

Table 33 showing the themes emerging from textual responses in Phase 1

Themes from textual responses
Hands-on
Doing it myself
Method
Theory/knowledge

Table 34 showing the themes emerging from student interviews in Phase 2

Hands-on / reality – this is the idea of being in a real world, where items can be touched and held. This is the concept of presence, being engaged in the experience.
Doing it myself / control – the idea that you have influence on the situation your actions cause things to happen. This is the concept of agency, being able to influence the experience.
Method / skills – this is the practical aspect of the activities, how things are done, practiced, sequenced and how skills are learnt.
Theory / knowledge – the theory, knowledge, understanding which is gained and the more abstract competences.
Trust / truth – the belief in the world they are part of, the verisimilitude of the experience, how the 'quality' of the truth is determined.
Risk / consequence – the things which follow from actions, the results which flow from decisions, in particular the possibility and consequences of failure.

Table 35 showing the Likert responses by teachers recorded for Phase 3

Survey questions to teachers	Percentage favouring VL / %
QT1. Do you agree your students learn more about the principles of scientific inquiry from virtual or physical laboratories?	13
QT2. Do you agree that students gain more understanding of theory through practical experience using real or animations / simulations / virtual laboratories?	37
QT3. Do you think that virtual laboratories teach students more practical skills, such as measurement and observation, than they learn in a physical laboratory?	13
QT4. Do you agree that students feel more motivated and engaged using a physical laboratory rather than a virtual laboratory?	0
QT5. Do you agree that students develop higher level skills and attributes, such as, communication, teamwork and perseverance, when using a virtual laboratory rather than a physical laboratory?	25

Table 36 showing the themes emerging from teachers textual responses in Phase 3

Hands-on
Real world
Additional resource
Learning tools

Table 37 showing the themes emerging from teacher interviews in Phase 4

Hands-on / reality
Doing it myself / control
Method / skills
Theory / knowledge
Trust / truth

CHAPTER 5

DISCUSSION OF THEMES AND FINDINGS

'Would you actually be a scientist?'

(Student G)

Introduction

In this chapter, I am attempting to bring together the themes which appear to run through the data. By doing this I hope to give some sort of answers to the research questions, as well as, illustrating the themes which have emerged. Using the literature reports and ideas which emerged in Chapters 2 and 3, as well as the research data, it is hoped to provide tentative answers to the research questions. The conclusions are drawn using an abductive approach or inference to the best explanation, as discussed in Chapter 3. Having said that, for a small-scale limited study such as this it is not always possible to draw firm conclusions, however the results do suggest some possible relationships and indicate areas for further study. In this chapter, each of the research questions is considered in turn. The material drawn on is selective and designed to answer each question in the way I think most appropriate at the time of writing. This may be different for other researchers or viewed from a different perspective. All conclusions are therefore provisional.

To begin with I examine the work of Putnam (1981) as it provides a useful framework which can be extended for this study. Putnam (1981) describes three schemata for scientific problems. These show how a given universal law can explain an observational fact, within given a context expressed which can be expressed as a set of auxiliary statements (AS). Putnam uses these schemas to categories different types of scientific activity. He describes how one, Schema I, shows the verification or falsification of theory and AS, given an observation.

Schema I

Theory

<u>Auxiliary Statements: S_1, S_2… etc.</u>

Prediction: true or false?

A second schema (II) he relates to Kuhn's 'puzzles' of normal science, where it is the influence of the AS which needs to be determined.

Schema II

Theory

<u>????</u>

Fact to be explained

While a third version (III) describes the prediction of a theory, given a set of AS and which Putnam (ibid. p. 71) says ‘is neglected because the problem is ‘purely mathematical’’. This is in fact the form of the VL, with predictions based on AS within a general theoretical framework.

Schema III

Theory

<u>Auxiliary Statements: S_1, S_2… etc.</u>

????

However, this study is dealing with a case not described by Putnam, in which we are searching for the underling theory which explains the observations. There are a number of potential AS, but we do not know which are important in determining the relationship between theory and observation. In these circumstances the reporting of a ‘thick description’ advocated by Lincoln and Guba (1985, p. 316) and Nowell et al. (2017), can provide a range of potential AS, for consideration. Following Putnam (1981) this case is proposed as Schema IV:

Schema IV

Theory: To be determined

<u>Auxiliary Statements: S_1, S_2… etc.</u>

Observation: O_1, O_2, … etc...

This is a form of the process of abduction which Peirce (in Hanson, 1962, p. 85) describes ‘Abduction consists in studying facts and devising a theory to explain them’ (see also Chapter 3): this is the situation we have here. To determine the underlining theory or theories is not a simple task, but as Kant says, ‘experience without theory is blind’ (Kant, 2024). In this work I am only attempting to illustrate some of the features which must be considered in pursuing this aim. In an attempt to simplify the process, I have focused on the answers to the three research questions posed in Chapter 3. These and the themes identified in Chapter 4 are used to frame the following discussions. Due to the limited scope of this work, there is much which could be explored, which is not, for example the application of Brinson’s (2015) KIPPAS method, the wider importance of tacit knowledge, Dewey’s method of inquiry or the application of Gestalt analysis, to VLs.

The emphasis of the analysis presented in this chapter, is largely informed by the works of Hanson (1962), Kuhn (1996) and Sennett (2009). These authors are concerned with the interaction of theory and practice. Hanson (1962) develops the idea of ‘theory-laden observation’ – how we see the world; while Kuhn (1996) extends this idea to discuss the framework in which scientists make their observations. Sennett (2009) takes a slightly different view, emphasising the interaction between the actor and the environment, reminiscent of the ideas of Dewey (1933, 2011), on inquiry as an interaction with the environment. The chapter continues by addressing each of the research questions in turn. While the sections are distinct, there is still significant overlap and in some cases the responses extend beyond the original questions.

RQ1: The extent to which students experience learning in a virtual laboratory as a mirror of reality?

In this section the idea of a 'mirror of reality' is explored. This is considered in the light of responses from students and teachers as well the literature. Sennett (2009, p. 84-85) develops the concept of the 'mirror-tool' and which has both the properties of replication and distortion. We need to consider the VL both as a 'replicant' – a true reproduction and a 'robot' – an enhanced version, better suited to education (this is considered under RQ3). So, the first task is to determine how much the VL replicates the real laboratory.

Similarities

Generally, VL are designed to provide a believable representation of reality and at a surface level this how the students see them. They will say *'I tend to believe it'* and *'what I've done on the virtual laboratory … equals what's been happening on when we do the experiments'.* While Teacher S feels *'they see things in real life, and they see that … it is a mirror of what we do in the lab'. … they can see that [the VL] is representing what we do in the lab, and I think they have no trouble with that concept as far as I'm aware'.*

So, students tend to believe both the real and VL are correct, expecting that results from both will agree. This can also be seen from the comments recorded in Table 38, showing a similar level of initial belief in the results of both laboratories Additionally, this is borne out by the studies cited in Chapter 2, showing similar learning outcomes in real and VL. Thus, the students' experience of both is they have a similar verisimilitude: in this sense the students' experience of both is similar. In the next section (RQ2), students' trust in both the VL and real laboratory is further explored.

Theory

From the responses of staff and students the main area where students seem to have a similar experience, in both laboratories, is that of theory. Comparing the VL to the real laboratory, one student says *'I would say the theoretical part is still there [for the VL]; it's just the practical side [missing]'*; they are identifying the similarity of the real and VL – in the theory. They also say, '*they're quite similar, cause you're still thinking about the reaction, you're still thinking about the same process that you know'.* There is a sense of practical theory, perhaps similar to the Aristotelian concepts of phronesis and praxis. However, there is a difference in that '*the learning will be slower … the links will be weaker',* while the real laboratory is *better 'for memorising cause you saw … everything'.* So, the learning experience is different even if the students feel they are learning the same thing. This can be related to the constructivist view of learning; knowledge will be built differently in the two environments. In the VL, students feel '*you can physically see the theory behind an experiment like you can see the particles'.* They are connecting their observations in the VL with the underlying theory. Hanson (1962, p. 19) tells us that 'seeing is a 'theory-laden' activity, in the VL this is made explicit – what is seen *is* theory. This likened to '*the process and the calculations that we had to do … the virtual laboratory is easier in terms of understanding things mathematically',* this part of the learning experience is the same or even better in the VL. Students are building knowledge based on the explicit theory built into the structure of the VL.

Differences

Learning in the real laboratory's rich more varied environment is not always the same as in the VL. This is this now explored through the topics, identified in Chapter 4, derived from the themes in the student responses. These sections focus on the differences between the real and VL, however, just as we focus on the differences between the English and French, rather than our greater similarity as Europeans, so we are more conscious of the differences between the laboratories.

Presence

Fans will spend hundreds of pounds to be present at live concerts and sporting events, rather than watching on television; perhaps this is part of a need to be 'in the room'. This also seems to the case with practical science. Teachers recognise that 'more senses are involved, such as touch and smell' in the real laboratory. While students say they *'like seeing things [with] my own eyes … playing out in front of me rather than just reading, … and watching a video and clicking buttons'* – *'it's engaging you completely like all your sense'.* Students' motivation is discussed below, here, it is the absorption in the moment which is significant. There is a sense '*when you're actually there doing it... making sure you're doing it right … you're more conscious';* perhaps you are even changing how you think*; 'you take a very different approach'.* This can be related to Kuhn's (1996) argument that there is a change in perception as the student spends time working with their subject. He gives an analogy to geography, 'Looking at a contour map, the student sees lines on paper, the cartographer a picture of a terrain. Looking at a bubble-chamber photograph, the student sees confused and broken lines, the physicist a record of familiar subnuclear events. Only after a number of such transformations of vision does the student become an inhabitant of the scientist's world, seeing what the scientist sees and responding as the scientist does' (Kuhn, 1996, p. 111). Students' F and G comments, link this to their studies in psychology '*we talk about schema … like little mental shortcuts. I guess we kind of do make these shortcuts; and then in the lab you might think, I've done this before, see made the shortcuts, so then you just can do automatically'… 'I think with the practical lab, you're thinking a lot more about each step and you're kind of taking in more and processing it'.* Sennett describes this process in a different way – 'Embedding stands for a process essential to all skills, the conversion of information and practices into tacit knowledge' (Sennett, 2009, p. 50). Immersed in a practical, students are, perhaps, starting to see more 'what the scientist sees' and 'respond as the scientist does'.

Students are aware of developing tacit knowledge (not that they would call it that) which they express through analogy *'it's like if you ask a chef to learn to be a chef without cooking … because science is so hands-on, it relates to everything around you'.* It is the practical aspect which seems to be the essential element since they feel if you are *'not applying that and not actually going through that yourself – Would you actually be a scientist?'* Sennett talks further about the 'constant interplay between tacit knowledge and self-conscious awareness, the tacit knowledge serving as an anchor, the explicit awareness serving as critique and corrective' (ibid, p. 50). While the students say '*although you know the theory, you can't apply it. It's like if it's like doing your driving theory test doesn't mean you can drive …you could get full marks on that, but you can sit in a car and not know how to drive'.*

There seems to be a recognition that practicals are '*good for exams because if I have a question that links to a practical, we've done, then my mind goes back to doing that practical I can remember'* there is a stronger link forged in the real laboratory, compared to the VL. There is tacit knowledge from doing – *'muscle memory almost'* which a student describes '*you're not quite sure how to say something, but you've seen it, you know what it is, so you can then describe it in a way that's might not necessarily be the way it's written in the textbook, but it can still get you marks'.* This is different sort of knowledge – tacit knowledge – which students feel they gain by presence in the real laboratory and is missing from the virtual experience.

Plato considers the imperfect images formed on walls of the cave, where a 2-dimensional image is more real to the prisoners than the 'real world' described by the returning prisoner. This is perhaps due to their *presence* in the 2-dimensional interaction – which they see with their own eyes, whereas the 'real' 3-dimensional world is just a second-hand story. In a sort of reversed scenario, the students say the VL *'definitely doesn't feel quite the same … because obviously you're just looking at it kind of one-dimension (sic)'.* For this student there is a difference between the dimensionally flat world of the VL and the real, rounded, world of the laboratory. They do not feel the VL is a convincing enough story to bring them into that world.

Interactions

There are two main interactions that students experience during practical activities: those with objects and those with people. Sennett says 'Good work … tends to focus on relationships; it either deploys relational thinking about objects or … attends to clues from other people. It emphasizes the lessons of experience through a dialogue between tacit knowledge and explicit critique' (Sennett, 2009, p. 51).

In order to understand what is happening both in the real and VL, I feel we need the concept of the 'near-present'; this is the period around the present moment – an instantaneous point which is perceived as 'now'. When we carry out an action it is a process which continues for some time – it is not over in an instant. Thus, Sennett (2009, p. 153- 155) tells us, the 'name for the movements in which a body anticipates and acts in advance of sense data is *prehension*' (ibid., p. 154). He talks of how the orchestral 'conductor gives directive hand gestures a moment ahead of the sound' (ibid., p. 155), leading the sound. Sennett then cites the work of Tallis in describing the actions of the hand as 'four dimensions: anticipation, of the sort that shapes the hand reaching for the glass; contact, when the brain acquires sense data through touch; language cognition, in naming what one holds; and last, reflection on what one has done' (ibid., p. 155). The students also feel this '*in the normal lab … you can hold onto it…on the virtual lab you can't do that… I kind of like the hands on…you can like touch it'.* They value being in a space where you are holding and *'touching, touching stuff, like it is all connected to your brain'* triggering recognition*, 'I know what that is …Where if you just touching … the keyboard, then it's just like – that's all.'* The contact with the keyboard does not trigger Tallis's processes, the anticipation is of a different shape, the contact is with a different surface, the naming is of something you are not touching, and the reflection is on two experiences – real and imagined. So, this process of prehension will not happen the same way in the VL and there is a danger it will be confused by mixed messages. This is similar to the concept of haptic encoding discussed by Rau (2020), which requires haptic cues to target specific concepts; this will not occur in the VL. Similarly, one teacher describes that in the real laboratory, students need to anticipate *'what you need to do at each moment, and how that actually all works together … that's something you can't really prepare for virtually …You sort of made that muscle memory'.* This point is also made by Sennett who suggests that 'To Tallis's four I'll add a fifth element: the values developed by highly skilled hands' (Sennett, 2009, p. 155).

For Sennett, (2009, p. 37) skills are 'trained practice' and it is only by 'going over an action again and again, [which] enables self-criticism' (ibid., pp. 37-38); however, 'modern education fears repetitive learning as mind-numbing' (ibid., p. 38). Practice both in the VL and the real laboratory is therefore limited by this philosophy and the demands of a wide-ranging curriculum which 'deprives people themselves from learning through repetition … understanding from repetitive, instructive, hands-on learning' (ibid., p. 39). A student also recognised this need for practice, commenting that, in the VL *'you don't practice the skills that you use in real life… it's mainly the manual dexterity part of it, you don't practice that'.* Here we see the motivation of the student through what Pink (2011) might describe as a desire for *mastery.*

Sennett also talks of 'tools' and how these shape imagination. The VL is one such tool, Sennett (2009, p. 194) says 'tools challenge us … it's hard to figure out how to use them'. Teachers describe VL as 'an additional tool to help explain how to carry out a practical but learners are often not very engaged with them and may not find them very entertaining or useful'. Additionally, 'they are a good tool to complement physical practicals' and can be '*a good tool – but it depends how the student uses it'.* While some students feel *'it's not actually there … just another screen tool'.*

Sennett develops his idea of tools promoting imagination by considering four stages. The first is reformatting, 'a process of reconstruction' (ibid, p. 210) – this is what the VL does – it reformats the experiment into a different space (and 2 dimensions) as Hobbes puts it 'the eyes shut, we still retain an image of the thing seen, though more obscure than we [actually] see it' (quoted ibid, p. 210). This is what the VL provides, the essence of the experiment.

This leads to the second stage for Sennett of 'establishing adjacency … twined presence…Two domains, the invisible and the palpable… brought nearer' (ibid, p. 210). Both of the tools in our case have been 'repurposed', experiments real and virtual designed to discover more about the world, now used to illustrate that knowledge, to teach, in a sense these are contrivances, chosen for their 'significance, relevance – these notions depend on what we already know' (Hanson, 1962, p. 26).

The third stage: is surprise, this is less obvious for VL, which appears to lead on from the idea of modelling a real experiment – but perhaps this is hindsight. Hanson (ibid, p. 67) says 'What is overlooked, however, is that experiments are *designed* to be as chain-like as possible'; Hanson sees a sort of conjuring trick '*contrived* to rivet attention on some select sequence' (ibid, p. 68). What is surprising then is that a 2-dimensional image on a screen makes students *'believe [the] virtual one is more reliable'* than the real experiment. '[D]rawn lines *should* be one dimensional' (ibid, p. 122), but cannot be used practically and so 'the almost invisible diagrams of geometry crept into physical thinking about atoms' (ibid). They feel the pattern presented by the VL is more compelling, of greater verisimilitude, than *'seeing things in my own eyes'.*

Sennett's 'final stage is recognition that a leap does not defy gravity' (Sennett, 2009, p. 211). The VL and real experiment are linked, chained together by induction. The VL makes no sense without the real experiment and yet since 'seeing is a 'theory-laden' undertaking' (Hanson, 1962, p. 19) without the theory expressed in the VL the real experiment makes no sense either. Both 'can enable us to take the imaginative leaps necessary to … guide us toward what we sense is an unknown reality latent with possibility' (Sennett, 2009, p. 213).

Sennett (ibid, p. 10) also talks of 'how resistance and ambiguity can be instructive experiences; to work well, every craftsman has to learn from these experiences rather than fight them … skill in physical practice—the hand habits of … using a knife … or puzzling instruments like the anatomist's scalpel'. This is reminiscent of student comments about the surprise of cutting into an alkali metal which felt like cutting a cake and for another the feeling of resistance to the knife was an important part of the experience of a dissection; while for a teacher '*different textures of … the things you're dissecting'* are a significant part of the experience.

Interactions also occur between people, thus, 'many students are stimulated by working together', while in the VL 'clicking mouse buttons can be done as individuals'. Teacher T feels that when working in the real laboratory *'your team is depending on something happening',* this builds *'the skills around*

… splitting of duties, washing up, cleaning up, getting things out' – how to act as part of a team. Sennett see this a part of a continuing way of working; 'Workshops present and past have glued people together … through mentoring … informal advising on the worksite; through face-to-face sharing of information' (ibid, p. 73); as one student says *'… if I don't get anything, I can just ask [another student to explain things] for me; online it's harder to do that'.*

The students *'like being around people, they like talking to people, they like interacting with them; and the physical, practical work allows all of that … it instils … camaraderie'.* Sennett (ibid, p. 7) also makes that observation that 'people working together certainly talk to one another about what they are doing … thinking and feeling are contained within the process of making'. He is suggesting the interactions enrich the process of making – that is learning to do a good job.

The experience of being in the laboratory Is also heightened by the presence of others *'in our labs there's tons of other people in there as well, so you've got to be careful about being with around other people, making sure everyone else knows what's going on'.* So, students *'feel like the personal aspect is definitely a lot different'* to working alone in the VL. In the laboratory there is 'the absorption into tacit knowledge, unspoken and uncodified in words, that occurred there and became a matter of habit' (Sennett, 2009, p. 77); interacting with objects in space and by watching and working with others, we ourselves develop. This point is discussed by Sellberg, Nazari and Solberg (2024) who say an 'important element of research will be … the nature of engagement that emerges in learning situations in terms of how students act, communicate with each other, collaborate in problem-solving and in manipulating the virtual environment'.

Motivation

The survey results for QS4 clearly show that students feel more motivated in the real rather than VL. This is echoed by the response of teachers to QT4 in their survey. There are probably a number of reasons for this related to presence and interaction which are discussed above, control and consequences which are discussed below: this section focuses on the role of achievement in motivation. Kuhn considers the motivation for normal science is 'in solving a puzzle that no one before has solved or solved so well' (Kuhn, 1996, p. 38); this could also be a motivation in the gamified VL (see Sus et al., 2020). However, there is much greater motivation reported for the real laboratory which is 'engaging you like completely with your skills, with your studies' and '*engages … your brain more'*. This contrasts with Hanson (1962, p. 30) observations of 'repetitious, monotonous … school-laboratory experiments'; hopefully practicals have improved since the middle of the last century.

For the VL our students they feel if '*you go wrong, you just knock a couple of points off*', and there is more motivation in the real laboratory where '*if you actually make a mistake in real life, it's gonna affect you'.* Some students feel they *'aren't engaged cause they're just staring at screen[s];* that '*there's no consequences to get it wrong … I feel like I'm more careless … it feels like I'm not really engaged'.* Similarly, the real laboratory *'feels a lot more rewarding because you've only got that kind of one chance when you do it right. You think, actually, I really enjoyed that outcome'* (this point is discussed in more detail, in Consequences, below).

In the real laboratory, there can be a sense of achievement in making, one student felt this and '*I went home and told my mother I've just made aspirin'.* Sennett (2009, p. 28) speaks of the 'craftsman's aspiration for quality' and 'poesis … 'something where there was nothing before' … because something suddenly comes into existence, it arouses in us emotions of wonder and awe' (ibid, p. 70). This is similar to Pink's (2011) concept of *purpose.*

Sennett (2009, p. 30) says, 'The carpenter, lab technician, and conductor are all craftsmen because they are dedicated to good work for its own sake'. He then explores the idea that 'good work means to be curious about, to investigate, and to learn from ambiguity' (ibid, p. 48). Similarly, teachers feel that students see the 'physical lab experiments are more variable, present more and different challenges', giving so 'a greater sense of achievement'. The students are then more motivated to do good work if they have options to control their learning and this is explored in the next section.

Control

Control can have more than one aspect; in this work two are considered. In this section the control that students feel they have in the actual (and VL) laboratories is discussed; a second aspect of control, that of the choice of the VL (and real experiments) is addressed in the next part, under RQ2.

Sennett (2009, p. 195) suggests we 'gain control, and indeed improve … skill [by having a] better understanding [of] our own powers of imagination'. This is not always the case in the VL where '*a lot of the times the steps are just on screen, and you just have to … move this to here and I need to mix that with that'.* The students are sometimes frustrated by this lack of control and indeed imaginative possibility, which Sennett describes as 'the limited, frustrating tool and the all-purpose sublime tool' (ibid): mirroring the limits of the VL compared to the possibilities of the real laboratory. While in the VL, *'everything is kind of guided and everything makes sense … but there's a bad side … sometimes it feels like you don't actually know what you're doing'.* Students are experiencing that difference between the limited VL tool and open-ended possibilities of the real laboratory.

For one student *'in practical [… laboratory, there are] skills you gain but in virtual one, there is no skill'.* This is echoed in the point that Sennett (2009, p. 52) makes, that 'Skill is a trained practice; modern technology is abused when it deprives its users precisely of that repetitive, concrete, hands-on training. When the head and the hand are separated, the result is mental impairment'. This just is what a student feels when using the VL '*because you're not really getting a hands-on experience, and sometimes it feels like you don't actually know what you're doing'.* Similarly, in '*the physical lab … is easier to understand how things actually work and how to control things better'.* If your choices affect the outcome, you are more motivated to understand what you are doing, this aspect of control is similar to Pink's (2011) autonomy (this is considered further in the next section).

Consequences

Consequences are the results of action (or possibly inaction); there several aspects to this. The first is causality – if A then B – students are taught this as part of HSW5 'recognising correlations and causal relationships'; this is part of the prevailing educational paradigm. This is an essential part of VL but is also part of the how the real laboratory is organised, based on induction. This is so ingrained into students' expectations, that cause and effect is a given. So, if things do not follow the expected pattern *'you repeat it three times'* and then you become *'suspicious about yourself'.* A second consideration is the effects of actions, this is related to control discussed above. Students can make things happen in the real laboratory which results in real consequences, and they are the agents of these. For example, working in the real laboratory a student recognises '*I have control over it from the beginning to end. I have control over deciding which apparatus to use, which reactants to use';* this is not the case for the VL *'where everything is kind of guided'.*

The third aspect is the sense of jeopardy, that actions in the real laboratory really matter. For most academic subjects there is the risk of not passing the exam, while for ‘chemistry the worst thing that can happen is death’ (CrashCourse, 2024). Students feel ‘*if you actually make a mistake in real life, it’s gonna affect you’ – ‘you feel pressure’.* As Dewey puts it ‘The living creature undergoes, suffers, the consequences of its own behaviour. This close connection between doing and suffering or undergoing forms what we call experience’ (from Dewey, 1920, quoted in Biesta and Burbules, 2003, p. 28). The students feel that there is a disconnect between the VL due to the lack of risk. In the real laboratory ‘*it feels more real, you take it more … seriously … [if] something goes wrong … you don’t know what the outcome’s gonna be … the risk is a really big factor between the two… so many risks that could go wrong, whereas the virtual’… ‘it’s like the consequences; it’s like if I do it wrong on the laptop, you can just redo it… In real life, … you’ve got do say’s two hours practical work’.* Students need to know that it really matters. This is a point made by Biggs and Tang (2011, p. 62) quoting that there should be ‘activities with an element of risk – physical, social or emotional – so that the experience is more real’. The VL does not provide that risk, reducing the experience so that you are *‘you are just looking at a screen … that’s not bothering me’,* while in the real laboratory *‘it feels a lot more rewarding because you’ve only got that kind of one chance when you do it right’.* Biggs and Tang (ibid) go on to say creativity occurs when ‘students are encouraged to take risks, to dare to depart from the established way of doing things’ (ibid, p. 265), rather than *‘just putting colourful substances with colourful substances and you don’t actually know what it is; there’s no consequences to get it wrong either’*. The VL is too constrained, too ‘right’ to allow for the edginess of what Sennett calls the ‘liminal zone between problem solving and problem finding’ (Sennett, 2009, p. 48). For Student G they *‘feel like it means a lot more to you to do it in the lab … You think, actually, I really enjoyed that outcome. You know, you tend to remember it more when you really enjoy it’*. Learning is an exploratory process and risk adds to the sense of adventure.

Brandon’s Matrix Approach

In Chapter 1, the interaction between presence and agency was explored using a matrix based on the work of Brandon (1994). This approach is now applied to explore the correspondence between experiences in different environments. Using Figure 6 showing the continua between the extremes of the agency and presence parameters, and the direction of the increase of experience. a pattern allows the location of both real and VL within a two-by-two matrix. Considering, as an example, the titration experiment based on the OCR PAG and the RSC screen experiment, preliminary estimates of locations within the matrix can be made as shown in Figure 26. Potentially, this could provide a framework for analysis. The difference in positions of the two points gives a measure of how well the VL matches the real laboratory. The line shown connecting them is therefore a semi-quantitative measure of the closeness of the representation. It might then be supposed that if the VL were altered to make it a closer representation, say by using video clips of real experiments, then the change in students perception of presence, could be measured by asking them to order how ‘present’ different representations made them feel. For agency, a similar process could be used, for example, by asking students to order different scenarios to identify in which they felt more agency. (In Figure 26 the positioning of the real laboratory is shown to be short of full agency as the students follow written direction, instructions from the teacher, as well as responding to interactions with other students and complying with safety rules). By separating the variables, it might be expected a clearer view of each could be obtained. The shortening of the line connecting the two points might then provide a more objective measure of the closeness of a representation.

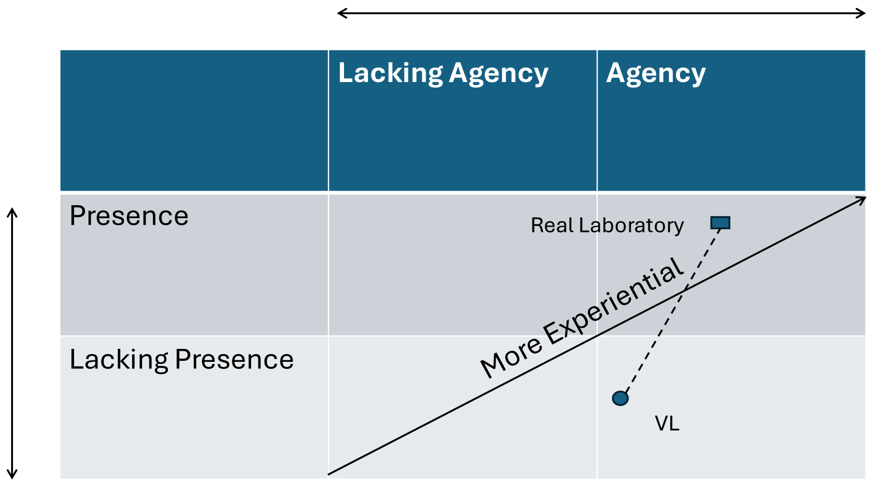

Figure 26 showing the estimated locations of the real and VL on the presence-agency matrix.

This type of analysis could be extended to examine the interaction between the parameters identified by thematic analysis in this work. For example, themes T1 – T6, identified in Chapter 4 could provide the axes for a number of two-by-two matrices or a large multidimensional matrix. The analysis could also be carried out using the derived parameters of theory, presence, interaction, motivation, control and consequences, presented in this chapter. This might highlight some of the different experiences of individual students, for example, anxious students may respond differently (to the responses recorded in this work) in terms of their motivation when plotted against consequences. The use of a Brandon-type matrix might help to illustrate these differences.

This approach could be formalised by imagining a function, $f(\psi)$ which represents student experience, where ψ, represents all possible influences on the students experience. We can identify then functions: one for the real laboratory, $f(\psi_{RL})$ and one for the VL, $f(\psi_{VL})$. If the experiences were indistinguishable, then $f(\psi_{VL}) = f(\psi_{RL})$ or $f(\psi_{VL}) - f(\psi_{RL}) = y$, where $y = 0$. In general, $|y| > 0$, so we would want to manipulate the ψ_{VL} to minimise the value of y. In this case we do not know all the values contained in ψ_{RL} or ψ_{VL} , however, we could approximate these to the features identified in the thematic analysis, e.g. T1,T2 … T6. Further investigation of this type of analysis is beyond the scope of this thesis but might prove illuminating.

The value in using Brandon’s matrix has been demonstrated in a study by Cullinane, Erduran and Wooding (2019) who investigated the focus of questions in GCSE chemistry examinations. These authors analysed examination papers and determined that questions can be categorised using the parameters of Brandon’s matrix. This reveals that the there is a disconnect between the expectations and ‘the finding … [that] illustrate how manipulative parameter measurement dominated the exam papers and how manipulative hypothesis testing type questions were present in a limited capacity … contrary to initial belief that manipulative hypothesis testing would be dominant, as this is often presented as ‘the scientific method’’ (ibid). Erduran, Ioannidou and Baird (2021) have also shown the use of Brandon’s matrix to analyse the use videos to develop students understanding of the scientific method. Their results show that Brandon’s matrix can provide a useful framework for the analysis of assessment questions, depending on the different parameters. These studies suggest that it is reasonable to use of Brandon’s matrix to carry out similar types of analysis.

Summary

The results suggest that the majority of the students feel a difference between their experiences in the real and VL. They recognise that there is value in their physical presence in the laboratory and being involved in real activities. They feel that they develop different skills though these experiences, compared to the VL. This could be related to the development of tacit knowledge, which can only be generated personally: this they achieve by *doing.* This is the type of knowledge which some students value as '*when you're actually there doing it... making sure you're doing it right … you're more conscious'*: this is different to that generated by *'having learned about it virtually and just looked at the theory of it'*. The experience and the knowledge are linked – *'you remember because … you create links in real life'.* This difference is also supported by the survey data which also identified differences between the experiences in the real and VL. There is motivation and engagement from being present in the room, rather than looking at '*just another screen'.* For both the students and teachers, presence in the real laboratory is different to that in the VL – it leads to different learning.

Similarly, both interactions with people and objects are identified as different in the real and VL. Students find that '*in the normal lab … you can hold onto it…on the virtual lab you can't do that… I kind of like the hands on…you can like touch it'.* There is motivation and engagement in handling items. Again, there is a different type of learning where students are *'touching, touching stuff, like it is all connected to your brain';* triggering recognition*, 'I know what that is'* – their experience and learning are different to the VL – '*just touching … the keyboard … that's all'*. Interactions with other people are also important in learning, students they feel that if you are *'just doing it individually, you're not gaining anything out of that, you're not talking to anyone or helping people out'.* Personal interaction is a significant factor for students' motivation, as is the sense of achievement generated by the *real* challenges of the laboratory.

Another factor which can have an effect on students experience of reality is the amount of control they feel they have in the two laboratories. Within the VL they feel that the lack control, they do not make choices and '*sometimes it feels like you don't actually know what you're doing'.* In the real laboratory they feel they have agency to determine the outcome of the experiment. This makes the experience more meaningful, whereas in the VL students feel *'you're not really getting a hands-on experience'.* Another significant issue is related to consequences. In the real laboratory the experience is enhanced by a sense of jeopardy – actions really matter. There are real consequences, even danger in the real laboratory. This is not experienced in the VL where '*there's no consequences to get it wrong'.* Theory is an area where the students feel they experience a similarity between the two laboratories. They '*say it's quite similar'* when thinking about the processes and theory.

In conclusion, there are basic similarities between the real and VL in terms of the replication of the experiment as a theoretical exercise. Students believe that the results they obtain in both laboratories are valid, so both true results (see RQ2 in the next section) and in this sense they have a similar experience. Explicit knowledge can be generated in both environments through revealing the actions of the underlying theory. However, there are a range of factors which affect students which appear to be absent from the VL, these can affect learning. Thus the generation of tacit knowledge only appears to happen through the experiences of the real laboratory. The reality experienced in the VL is then more the 2-dimensional image in Plato's cave (Russell, 2000, pp. 140-141; Kenny, 1997, p. 25) lacking form and colour; while the real 3-dimensional laboratory has many more subtle possibilities which can stimulate and enhance learning.

RQ2: The extent to which students regard the results of experiments conducted in these environments as trustworthy?

In this section the idea of trust is explored, why do student believe in what they are told about the VL or real laboratory or anything for that matter? Education is based on certain pillars of trust, that we can believe what we are told. This trust is explored in context of practical science, and in particular, the VL.

The VL is developed within what Kuhn (1996, p. 42) describes as a *paradigm* – a 'strong network of commitments – conceptual, theoretical, instrumental, and methodological'. This is an 'implicit body of intertwined theoretical and methodological belief' (ibid, pp. 16-17), thus 'even what counts as a fact is determined by the paradigm' (Shapere, 1981, p. 36). An example of this, is the description of the relative motions of the Sun and Earth. When we look out the window each day, we clearly see it takes one day for the Sun to travel around the Earth: this is the geocentric view. However, in schools there are 'Statutory requirements [that] Pupils should be taught to: describe the movement of the Earth, and other planets, relative to the Sun in the solar system … and the apparent movement of the sun across the sky' (National Curriculum, 2013, p. 29); so, the Earth takes one year to travel around the Sun: this is the heliocentric view. Kuhn (1996, p. 149) describes this *Gestalt switch* as 'a whole new way of regarding the problems of physics and astronomy', changing the 'meaning of both 'earth' and 'motion'. Without those changes the concept of a moving earth was mad' (ibid. p. 150). However, Einstein tells us all motion is relative, so the concept of the Earth moving around the Sun and the Sun moving around the Earth, become in some way the same: there is no privileged position in the Universe. Kuhn (ibid., pp. 101-103) describes these shifts to new paradigms as 'incommensurable with that which has gone before' (ibid., p. 103). A similar Gestalt switch occurred from the Julian to Gregorian calendars, described in Chapter 3, some days simply did not exist.

In a way students see the switch between theory and practice as a Gestalt switch *'it's like if you ask a chef to learn to be a chef without cooking, it's like, because science is so hands-on, it relates to everything around you'.* They accept the paradigm of practical science: they seem to have the empiricist's view *'I like seeing things in my own eyes'* and *'you see all the process in front of your eyes, so even you can feel the temperature, you can see the colour change … you feel you learned all this and you saw the experiment'* also *'cuz I've actually done it … and they're the results I've got from my own experiment'.* Similarly, teachers report that *'sometimes [students] trust … more because they saw it happen with their own eyes'.* This goes further in that although students may trust the theory, they feel that '*although you know the theory, you can't apply it. It's like if it's like doing your driving theory test doesn't mean you can drive … [you] could get full marks on that, but you can sit in a car and not know how to drive'. 'So, you could explain the whole of chemistry, but … you can't do it' – 'Would you actually be a scientist?'* This is also part of the point made by Shulman (2005) discussed in Chapter 2, that there are 'signature pedagogies' which are integral to the paradigm of science we teach (this is discussed further, below).

Moreover, Kuhn (1981, p. 22) maintains that 'scientific concepts are invariably encountered within a matrix of law, theory, and expectation from which they cannot be extricated for the sake of a definition' and that 'those concepts were not intended for application to any possible world, but only to the world as the scientist saw it'. This is the environment in which Kuhn (1996, p. 42) suggest 'normal science' will occur through 'puzzle solving. Because it provides rules that tell the practitioner … both what the world and his science are like'. This then is the scientific world our students inhabit, created for them through the education system, which requires them to:

HSW4 Carry out experimental and investigative activities, including appropriate risk management, in a range of contexts;

HSW5 Analyse and interpret data to provide evidence, recognising correlations and causal relationships;

HSW6 Evaluate methodology, evidence and data, and resolve conflicting evidence

(see Chapter 2).

This sets a paradigm for the 'normal science' taught in schools, which might be viewed as largely empiricist and relying on inductive logic.

What is truth?

How do we decide what is true? If we now focus on the VL, which exists as a constructed world, within a paradigm, we have to ask who chooses the paradigm? Here our students' experiences can inform the discussion. As we saw in the responses in Chapter 4, T5, students appeared to identify 4 sources of truth. Each of these has an influence on the paradigm which prevails, and so who has control of the 'truth'.

External authority

Lakatos (1984, p. 94) tells us: 'truth lies in power', and this also what the students report. They identify the reliable sources of VLs as powerful institutions such as universities or the RSC, a *'big website with credibility'*; and teachers believe that VL are produced by *'quite reputable universities or companies*'. The students also believe that '*professors or doctors', 'people who they had experience and experts … scientists who've been doing it a lot of years'* have created these VLs. For Kuhn (1996, p. 64), these are the group who are working within 'normal science', they are invested in the paradigm so offer 'considerable resistance to paradigm change'. The paradigm perpetuates itself and the VL is the perfect vehicle for this, as it has a fixed outcome always consistent within the theories on which it is based. The results produced by the VL depend on the choices made by its creator which Kuhn tells us are 'determined jointly by the environment and the particular normal-scientific tradition [they have] been trained to pursue' (ibid, p. 112).

For science, Kuhn identifies 'As the source of authority, … textbooks of science together with both the popularizations and the philosophical works modelled on them' (ibid, p. 136). He then suggests that 'All three of these categories … have one thing in common. They address themselves to an already articulated body of problems, data, and theory, most often to the particular set of paradigms to which the scientific community is committed at the time they are written' and 'All three record the stable outcome of past revolutions and thus display the bases of the current normal-scientific tradition' (ibid, p. 136). However, Popper (1981, p. 98) fears that 'even a scientific theory, may become an intellectual fashion, a substitute for religion, an entrenched ideology'. Kuhn extends his thesis to state, possibly more controversially, 'The very existence of science depends upon vesting the power to choose between paradigms in the members of a special kind of community. Just how special that community must be if science is to survive and grow may be indicated by the very tenuousness of humanity's hold on the scientific enterprise' (Kuhn, 1996, p. 167).

Focusing again on VL this can be considered, to be normal science, based on a specific paradigm – which the students accept for various reasons. The National Curriculum and the exam boards, re-enforces this paradigm with 'How Science Works'. This is self-perpetuating in two ways: first as Hanson points out observations are theory-laden we are taught and then ourselves teach, to view things in a certain way and secondly, dissent from the paradigm is met with low marks and exam failure – barring progression in the field and a platform for an alternative view. If the choice of VL depends on the prevailing paradigm, as suggested above, then this choice belongs to a 'special community', moreover 'if authority alone, and particularly if nonprofessional authority, were the arbiter of paradigm debates' (ibid, p. 167) then would the VL be chosen on scientific grounds at all?

Integrity

The second area is related to a trust in natural honesty and scientific integrity. There is a feeling from students that because the VL was *'was made by scientists, so it's accurate'* and '*what reason do they have for it to not be right?'* and *'what would be their game? Especially a scientist, you always wanna get the best end result'.* The students seem to be crediting the scientists with the virtue of phronesis. Carr (1995) describes phronesis as 'the virtue of knowing which general ethical principle to apply in a particular situation. For Aristotle, phronesis is the supreme intellectual virtue and an indispensable feature of practice. The phronimos — the man of practical wisdom — is the man who sees the particularities of his practical situation in the light of their ethical significance and acts consistently on this basis' (ibid, p. 71). Moreover, Lakatos (1981, p. 108) describes the rules for acceptance or rejection of a theory *'as a code of scientific honesty* whose violation is intolerable'.

However, there is also honest mistake, as one teacher reported for a real experiment *'that just went totally wrong, and we got the complete opposite relationships and what we shouldn't be seeing. And I can't help thinking that either … the technician or some something went wrong somewhere in the dilution, and either were labelled maybe, and that could have been why it went wrong'.* So, we cannot always rely on experiments and even 'the work of such men as Galileo and Newton have been found to be riddled with errors' (Shapere, 1981, p. 33). There is also honest confusion over the meaning of theory, Hanson describes five different interpretations of Newton's second law which he says a 'physicist on a single day in the laboratory may use … in all the ways … without the slightest inconsistency' (Hanson, 1962, p. 100); so, honesty does not guarantee truth.

Chain of authority

The third concept is that of authority, Sennett describes the authority of the master craftsman as part a hierarchy 'masters, journeymen, apprentices' (Sennett, 2009, p. 58), part of the medieval guild system. Perpetuated today through institutions such as the Royal Society of Chemistry and the universities which validate the skills and knowledge of the 'master'. The masters now are the professors, lecturers and teachers who vicariously relay the received wisdom of the age. Students, the new apprentices, accept this *'because it's kind of what we've taught, to follow people above us … it's kind of expected of you'.* We are all are part of Kuhn's paradigms, fitting into a pattern of that which is acceptable within our field – 'normal science'. Sennett describes that in the medieval workshop the 'master's verdicts were final, without appeal' (ibid., p. 58); despite the fiction of 'academic freedom', there is today, a clear set of expectations set out in the qualification specifications ('*just to make sure they're right for OCR')*, HSW, OFSTED, employers ('*I could get myself into a lot of trouble for saying'*) and the directions of the Department for Education. There is an expectation by both teachers and students that science will be taught in a 'scientific way' following accepted principles.

This chain of external authority is shown schematically in Figure 27. The students recognise this chain of authority '*you've got a status above us, so we kinda believe ... You've got like a higher authority than us … whatever you say, we go – Okay'*, but maybe not its source. They have been taught and accept that *'if my teacher directed me to it, then I believe the teacher to be right''* Again, 'truth lies in power' (Lakatos 1984, p. 94) and the truth which is passed on belongs to the paradigm which is accepted. 'These are the community's paradigms, revealed in its textbooks, lectures, and laboratory exercises. By studying them and by practicing with them, the members of the corresponding community learn their trade' (Kuhn, 1996, p. 43). This is also the view of Sennett (2009, p. 69) who says, 'Authority in the generic sense relies on a on a basic fact of power: the master sets out the terms of work that others do at his direction … in the medieval workshop or the modern scientific laboratory'. While, Feyerabend (1981, p. 157) comments on 'the role science now plays in education. Scientific 'facts' are taught at a very early age and in the very same manner in which religious 'facts' were taught only a century ago. There is no attempt to waken the critical abilities of the pupil so that he may be able to see things in perspective'.

The problem of complexity, discussed in Chapter 3, is also relevant to this discussion. We become reliant on "experts" to interpret many of the aspects of technology and science. The VL are often built on a complex set of assumption and theories. It does not seem that these are often explicitly shared with users and may not even be fully understood by those constructing the VL. Certainly, students at level 3 would struggle to understand the interactions between theories and assumptions which are contained within even a relatively simple VL. In truth most teachers are in the same position and so also rely on their trust in the "expert" organisations producing the VL. The ethos of an educational institution or learned body can also exert influence how complexity is addressed. Additionally, the concept of a signature pedagogy developed by Shulman (2005), directing the expected course of learning, may also be relevant here and is discussed in more detail below, under RQ3.

The role of the teacher

An area where students experience this chain of authority is their trust in the teacher. Sennett (2009, p. 53) suggests '[m]ost scientific laboratories are organised as workshops' where 'assistants in it undoubtedly learned from the example of their masters' (ibid, p. 74). For students, it is part of the education system, *'we've taught to follow people above us … it's kind of expected of you'.* They are conditioned to accept that, as a teacher, '*you've got like a higher authority than us … whatever you say, we go – Okay' 'and if my teacher directed me to it, then I believe the teacher to be right*'. Kuhn (1996, p. 80) tells us that the 'science students accept theories on the authority of teacher and text, not because of evidence'; this 'is part of learning the paradigm at the base of current practice'. This is the 'traditional' role of the teacher as described by Carr (1995). Students have confidence in their practical work as well, because *'you've got like a tutor as well … I guess it's always that like guideline of where we should be'.* The students also credit their teachers with the virtue of phronesis. So, teachers feel, students '*would think … the lesson will have been sculpted in some way … and the practical work would reflect that'.* When using a VL *'I think that's because they would trust me, to not … [to] allow them to go … on a wild goose chase … go off on a tangent and get ridiculous results'.* There is a mutual expectation that the teacher will do the best for the student (exploration of this point is beyond the scope of this thesis).

Teachers are part of this same system, they trust the authority of the VL on the same sort of basis as students, that they are from *'reputable universities or companies'* and *'trust … that they have done their research, and they've got everything right'.* However, they *'always sort of check through them',* this adds a layer of confidence for staff and so for students too, that – '*He's not gonna give us a program that would just give us … nonsense results, irrelevant results'.* The teachers feel they provide a *'quality assurance test'* so that they are *'confident that [it] explains things correctly'* and *'not really* *found any that are wrong'*. However, there can be issues with this reliance both in the real and virtual worlds. For example, one teacher found '*we did have an experiment that just went totally wrong … and I can't help thinking that either … the technician or some something went wrong somewhere in the dilution, and … were [mis]labelled maybe, and that could have been why it went wrong'.* Similarly, students say *'the lab techs are great, but how do I know what … they're putting that in that bottle? … how are they a hundred percent sure that the company is sending you hydrochloric acids? It's label's hydrochloric acid. How are you a hundred percent sure that's that … it could be mixed in with something else and you would just never know'*. Another student said *'We get some like HCL 0. 1 molar, but that one is not reliable … probably the stuff we got it, they are not reliable or with different molar or concentration …, we cannot try and test all of… this material we get'.*

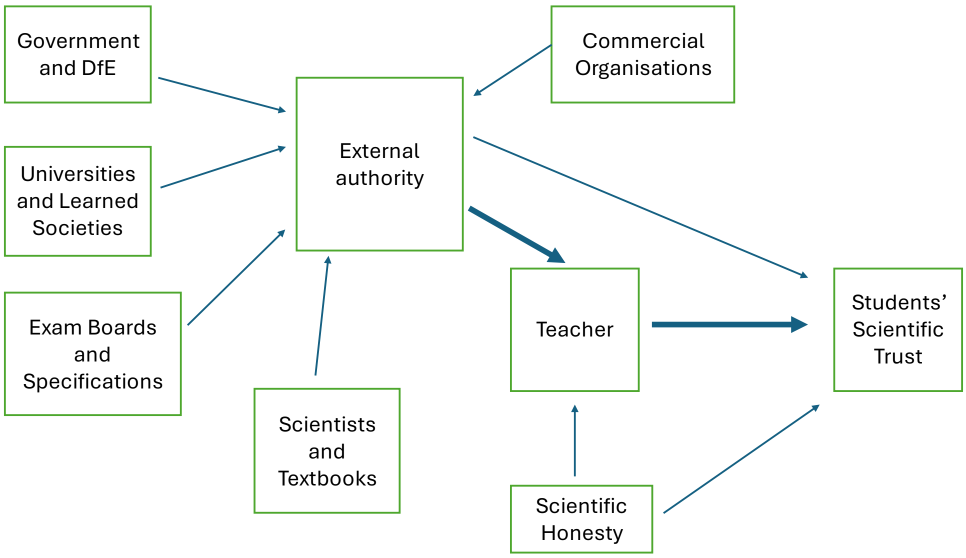

Figure 27 showing a schematic of the influences on students' trust due to external authority

Empirical evidence

The fourth area of trust is that of the observations by students themselves – '*cuz I've actually done it … and they're the results I've got from my own experiment'*. In the real laboratory '*you see all the process in front of your eyes …it's engaging you completely like all your sense. And you feel more confidence when you do the experiment, when you finish because you feel you learned all this and you saw the experiment'.* One student says '*you were there when it happened … Whether it's right or not, they are the results you would get cuz that's what you did'.* Also, there is confirmation from others *'if you're in a classroom full of people doing labs, there's other people doing it as well. So, if you go, oh, what did you get?'* They trust the results of the VL, because when comparing them to their real results, '*this equals what's been happening on when we do the experiments'.* While one student feels, *'because I follow the right steps and compare results with the people, and the virtual laboratory and it seems accurate'.* However, Hanson (1962) would argue that these observations are 'theory-laden'. They are only true within the context of the theoretical landscape of the observer, 'theories and interpretations are 'there' in seeing from the outset' (Hanson, 1962, p. 10). He develops this idea, as discussed in Chapters 2 and 3; one example is the X-ray tube, he asks if a trained physicist would see the same thing as school pupil or a baby. He answers 'Yes – they are visually aware of the same object. No – the ways in which they are visually aware are profoundly different' (ibid., p. 15). This is what the students experience in both the real and VL, '*seeing things in my own eyes … what's in front of me'.* However, '*if someone said … do a reflux, you could tell 'em the whole … step-by-step routine of how you do it. You give them … a Quick-Fit set and they look at it and they go, how do I stand it up?'*, without the background knowledge and experience the experiments do not make sense. So, the students see what they are looking for: *'you can see the colour change, … but … we mainly think about the reason about the reactions, what's happening'.* Students seem to recognise this link to theory in the VL, *'because you can physically see the theory behind an experiment like you can see the particles'* and *'seeing how things actually work in terms of maths and equations and what's going on with the particles'.* Another talks of the development of a world picture based on theories where *'starting in a virtual laboratory is good, [it] help[s] build knowledge and … applying it in real life'.* This aligns with Hanson's (1962, p. 30) view that 'physical science is not just a systematic exposure of the senses to the world; it is also a way of thinking about the world, a way of forming conceptions'.

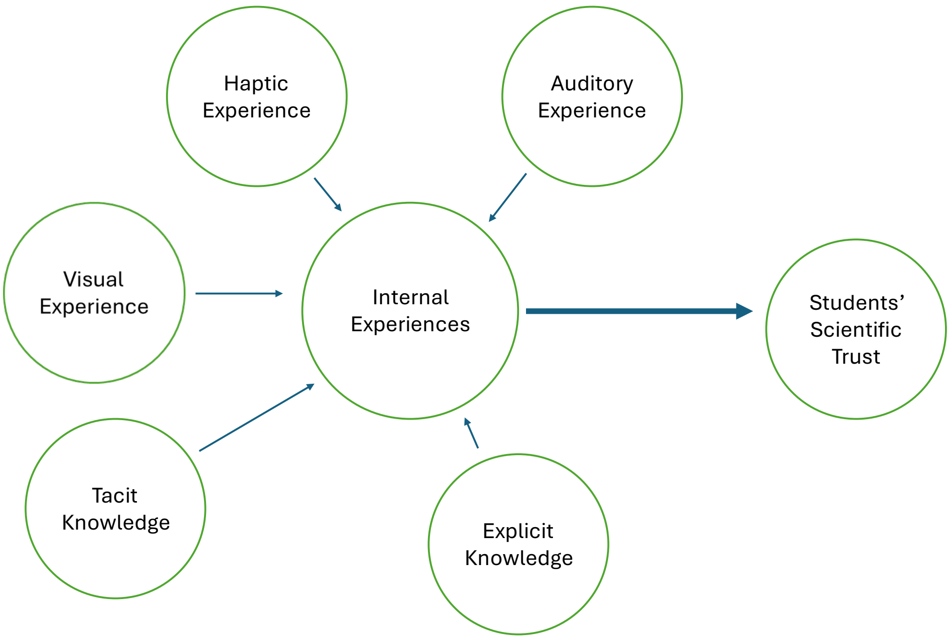

Figure 28 showing a schematic of the influences on students' trust due to internal experiences.

Truth in theory

We can consider a theory as corresponding to a set of patterns – we compare our experience to that set of patterns – if it matches – we say we understand, if it does not match – we say we do not understand. If we then change our theory/pattern to be closer to our experience – we say we have learnt. Kuhn (1996, p. 47) suggests that 'the process of learning a theory depends upon the study of applications, including practice problem-solving both with a pencil and paper and with instruments in the laboratory. If, for example, the student of Newtonian dynamics ever discovers the meaning of terms like 'force,' 'mass,' 'space,' and 'time,' he does so less from the incomplete though sometimes helpful definitions in his text than by observing and participating in the application of these concepts to problem-solution'. We are developing and testing the patterns we come across in these situations. Each student will develop their own version based on the ever-changing confluence of their experiences (see Figure 28).

We can then think of *theory* as the formalisation of patterns, patterns are what we use to recognise things, we have innate, tacit patterns as well as explicit ones. Explicit patterns lead to theories, tacit patterns lead to intuition. We hold both as part of our mental apparatus, both learnt and innate. Popper (1981, p. 84, n. 7) talks of an 'organism's repertoire of behaviour', which might be considered as the patterns which the organism has available to interact with the environment. He suggests (ibid. p. 85, n. 9) 'our perceptions [are] 'made' by us, by decoding (comparatively 'given') clues. The fact that the clues may mislead … can be explained by the biological need to impose our behavioural interpretations upon highly simplified clues'. He continues with his 'conjecture that ou[r] decoding of what the senses tell us depends on our behavioural repertoire'.

Kuhn (1996, p. 206) says the reason 'a scientific theory is usually felt to be better than its predecessors not only in the sense that it is a better instrument for discovering and solving puzzles but also because it is somehow a better representation of what nature is really like. One often hears that successive theories grow ever closer to, or approximate more and more closely to, the truth. Apparently generalizations like that refer not to the puzzle-solutions and the concrete predictions derived from a theory but rather to its ontology, to the match, that is, between the entities with which the theory populates nature and what is 'really there' … 'Perhaps there is some other way of salvaging the notion of 'truth' for application to whole theories, but this one will not do. There is, I think, no theory-independent way to reconstruct phrases like 'really there'; the notion of a match between the ontology of a theory and its 'real' counterpart in nature now seems to me illusive in principle.' Similarly, Lakatos (1984, pp. 188-189) gives an interesting discussion on two interpretations of verisimilitude, which he says is 'intuitive truthlikeness of the theory; in this sense, in my view, all scientific theories created by the human mind are equally unverisimilar and 'occult'. Secondly, it may be used to mean a quasi-measure-theoretical difference between the true and false consequences of a theory which we can never know but certainly may guess. It was Popper who used 'verisimilitude' as a technical term to denote this sort of difference'. Lakatos' view then seems to be at odds with the VL ever being a true representation, he cannot see theory matching the truth; but a process in which theory more closely approaches truth maybe possible. Thus, verisimilitude is likened to praxis, a process of doing, rather poesis, making something which is truthlike.

From these ideas it would seem that whatever we experience as 'real' or 'true' is so tied up in our theories that it does not have a separate existence. Feyerabend (2010, p. 151) goes further, for him 'Experience arises together with theoretical assumptions not before them, and an experience without theory is just as incomprehensible as is (allegedly) a theory without experience'. In some ways students see this with the VL as an embodiment of theory, '*because you can physically see the theory behind an experiment like you can see the particles'.* However, the students see theory as distinct from practice, they feel that for the VL *'the theoretical part is still there … it's just the practical side [missing]'.*

Truth in practice

For Putnam 'practice is primary' (1981, p. 78), he expands this idea by saying 'We judge the correctness of our ideas by applying them and seeing if they succeed; in general, and in the long run, correct ideas lead to success, and ideas lead to failure where and insofar as they are incorrect' (Putnam, 1981, p. 78). This is a clearly empirical view with which most of our students would agree – if '*we had repeated the experiment multiple times and we got the same result, then I probably trust what we did'.* However, their trust is tempered by a lack of confidence in their own abilities – *'I'm gonna be sure I've done something wrong then'* or in the materials they are working with – '*the materials they could be reliable or not'.* When looking at students views about observations they like *'seeing things in my own eyes'* and *'seeing how things are playing … out in front of me'.* However, Hanson (1962, p. 19) says 'seeing is a ‘theory-laden’ undertaking. Observation of x is shaped by prior knowledge of x.’ Our empirical observations are moulded by our previous experiences. We make sense of the world by fitting it to the patterns we already know, learning is then increasing our library of patterns against which we can know the world. The VL is a pattern, a model it can take us so far in our journey, but we will outgrow it (hopefully).

In a sense the VL is embodiment of theory, ‘*because you can physically see the theory behind an experiment like you can see the particles’.* There is a sense of practical theory, perhaps similar to the Aristotelian concepts of phronesis and praxis; Carr (1995, p. 67) says ‘praxis has a meaning roughly corresponding to our term ‘practice’, however ‘in its classical context, ‘practice’ referred to a distinctive way of life – the bios praktikos — a life devoted to right living through the pursuit of the human good. It was distinguishable from a life devoted to theoria (bios theoretikos) – the contemplative way of life of the philosopher or the scientist – in terms of both its end and the means of pursuing this end’. Carr then considers the distinction ‘between two forms of human action — praxis and poiesis — a distinction which can only be rendered in English by our much less precise notions of ‘doing something’ and ‘making something’’ (ibid, p. 68). This is interesting distinction in terms of practical education. The real laboratory includes both praxis and poiesis – there is action, students are learning though doing, developing skills (a human good); but also, things are made, reactions happen new compounds are formed. Chemical reactions have products – they change the world. However, in the VL there is still praxis, skills can still be learnt, but there is no product – apart from the movement of a few electrons the world is left unchanged. Students recognise this in their engagement with the real laboratory, their actions have consequences – they may even make aspirin. Carr’s main concern is educational practice, the overall framework and philosophy which directs education. Here we are just concerned with practical science education, but this might help to illuminate the overall picture. Carr describes the concept of phronesis as ‘practical wisdom’ (ibid, p. 71) which guides the implementation of praxis. This is part of what I see as the aim of the student practicals, not just learning skills and illustrating theory, but a way of being a scientist. One student says, *‘would you actually be a scientist … because although you know the theory, you can’t apply it?’;* without ‘practical wisdom’ you cannot understand a 3-dimensional world. The student gives the example of passing the *‘driving theory test doesn’t mean you can drive … you could get full marks on that, but you can sit in a car and not know how to drive’*. This is the Aristotelian distinction between distinction between ‘techne … technical knowledge or expertise’ (ibid, p. 68) and phronesis. In the student’s example, the difference is between knowing that you need to stop at a red traffic light (techne) and judging (and applying – praxis) the correct pressure to the brake pedal to bring a car to a smooth stop at the red light (phronesis). Phronesis may also be seen in the real laboratory where ‘*some practicals take a really long time. If it goes wrong … you’ve got do say’s two hours practical work’,* students have to make real choices about how they work – ‘*doing things more carefully and accurately’.* They feel *‘it’s the fact that [it] can go wrong. So, I really need to make sure I’m doing the right things’ … ‘I think you put a lot more thought into it’*. There is no real opportunity for this in the VL where *‘you just knock a couple of points off’* and ‘*you can just redo that level’*. There is less incentive for considered action when you are ‘*just scrolling mindlessly and clicking mindlessly in a virtual lab’.* However, how can we rely on the empirical evidence to support the VL when this evidence is ‘theory-laden’ by the very theories on which the VL is built?

Dual paradigms

Although dual paradigms are not discussed by Kuhn explicitly (suggesting on the section on paradigm choice (1996, p. 94, 103, 104) that a single paradigm is chosen) however, he does talk of Gestalt switches (e.g., ibid, p. 111-114), which I feel can only be possible if you can view two incompatible interpretations almost simultaneously. They both make sense individually, the change between the reported observation is in the mind of the observer, so could exist in separate, concurrent paradigms. Popper (1981, p. 85) and Kuhn (1996, p. 85) both accept the reality of the Gestalt switch. In order to have a Gestalt switch both states must be accepted solutions to the problem. You need to believe it is a duck one minute and believe it is a rabbit the next, both must be possible, not simultaneously, but contiguously and reversibly. Considering now a Gestalt switch between patterns, two or more patterns need to be available simultaneously (e.g. the counters example, in Chapter 3).

However, what happens when new data or a new theory are introduced. This can lead to a crisis when new data will only fit one pattern; or for Popper, will not fit a pattern – therefore falsifying its validity. In this situation *learning* occurs, one pattern is falsified, the other left as a possible match. Logically, Popper says, we discard the falsified pattern; however, for Kuhn the choice is not so clear. An example is the series 3, 5, 7, 11, 13 – is this the first primes missing 2 or the first odds missing 9? We take the patterns in our heads and superimpose them on the data to make sense of it. If we only know about odds, and not primes, this is our paradigm – the pattern fits (almost) 5 out of 6. Then if we know about primes and not odds, a perfect fit just limited data. It is easy to see that two people looking at the same data see different things, based on the theory they use (or the pattern they see). This is also pointed out by Hanson (1962, p. 18) who describing the response to the heliocentric model, says 'Most people today see the same thing at dawn in an even stronger sense: we share much knowledge of the sun. Hence Tycho and Kepler see different things, and yet they see the same thing. That these things can be said depends on their knowledge, experience, and theories'. If you know about odds *and* primes, then there is the possibility of a Gestalt switch, 'seeing as' in two different ways. Perhaps, this is why two people seeing the same thing, can see it as very different. So, two children, one who has only played football, the other only basketball, would be perplexed by the others response when encountering a ball: in a sense, the responses would be incommensurable.

Potentially, incommensurability is an issue in teaching where the educator is (generally) invested in the paradigm which validates the instruction. At first, the student does not hold the pattern in their head which would allow them to 'see as' (Hanson, 1962, p. 19) the teacher. Education in this case is giving the student the theory – the pattern, which allows them to unlock the data and 'see as'. This process is more explicit with the VL. Here there are a set of theories which work in a particular way which literally allows the student to 'see as'. In the real laboratory, the students see a long glass tube with numbers printed on it as *a burette*. In the VL they see a series of lines as *a burette*. Hanson (ibid, p. 19-30) describes in some detail the idea of 'seeing as', which requires a pre-knowledge of the object. Moreover, Babbage (quoted by Hanson, ibid. p. 30, n. 1) talking of the Fraunhofer lines, says 'You will look for them and not see them … I will instruct you *how to see them*, and you shall see them, and not merely wonder you did not see them before, but you shall find it impossible to look at the spectrum without seeing them'. We identify what we see, by what we already know, or what we are taught. Hanson extends this to the different idea of 'seeing that', in this case, 'seeing that' a burette can deliver a known quantity of solution. The student needs to 'see that' (the burette measures solutions); as well as, to 'see as' (a burette – some particular glassware or a collection of lines). If both these conditions hold, then learning in the VL will be the similar to that in the real laboratory.

These two versions of the laboratory, real and VL, seem to roughly align with the traditional and liberal teaching perspectives described by Carr (1995, p. 55) and shown in . The VL has some of the attributes of the traditional perspective e.g. experts transmitting objective knowledge, which is tested; while the real laboratory is closer to the liberal perspective e.g. discovery methods of personal learning with qualitative assessment.

Students do not seem invested in a single paradigm, as Kuhn claims scientists are, they seem happy with multiple views, but science insists on the 'right answer' – that is, the one which fits the predominant paradigm. This is what the students are taught in science – the way of the specification and textbook. VL is the 'practical' expression of this; the practical version of this paradigm. Normal science reinforces the patterns by repeated example, excluding 'anomalies'. Experience in the real laboratory leads to a second view based on empirical experience. This creates what could be seen as a dual paradigm. How this influences students trust is shown in Figure 29, indicating that external authority is the main source of trust underpinning the VL, while internal experiences provide the main source of trust of the real laboratory. Additionally, there are minor influences which affect this picture (observations are theory-laden and the VL is also in some sense, experienced by the students).

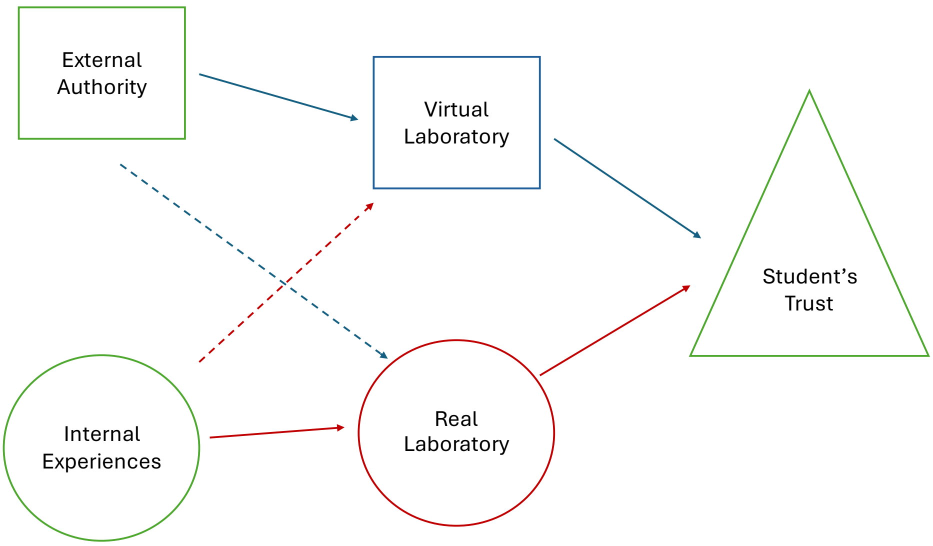

Figure 29 schematic showing the influences on students trust in the real and virtual laboratories.

Full lines indicate the main source of influence, while the dashed lines indicate minor contributions, see text for further details.

The students' acceptance of a dual paradigm can be illustrated by students' responses to questions about a potential conflict between real practicals and VL. Student C's initial view was '*I say strongly believe'* in the truth of the VL and that a conflict between real and VL would cause real distress. This has been explored more in Table 38, which summarises students' views, and then analysed in Table 39.

Table 38 showing a summary of the student's belief in real and VL, together with the response to having to choose which to believe

Student	Belief in VL	Belief in real practical	In the event of a conflict
Student A	*one from RSC … yeah. But if it's just this random [person] …*	*No, because it's us.*	*Like 60%, like belief in myself and 40 in the virtual*
Student B	*as long as it is from a trusted person or place*	*[if] we had repeated the experiment multiple times and we got the same result, then I probably trust what we did*	*60 / 40 – 60 % trust in myself*
Student C	*strongly believe*	*Because I follow the right steps and compare results with [o]the[r] people*	*70%, my results.*
Student D	*Much reliable, about reliability*	*you cannot trust yourself, because … the materials still not, they could be reliable or not.*	*STUDENT E: They're not reliable …* INTERVIEWER: So, you can't trust anything? *STUDENT E: Exactly. It's how it stands.*
Student E	*I tend to believe it*	*if you do it, you know, you've seen …*	*I definitely check my results before I become sceptical about the virtual laboratory*.
Student F	*I guess in a way you can be like, you can, I don't, I feel like you do trust them.* but also … *They know what they're doing type of thing.*	*I think sometimes getting wrong and getting the wrong results is kind of good in a way.* *So, then you learn from it next time.*	*I guess you back go back to the lab.* *I can't keep getting it wrong.*
Student G	*I don't think I trust them as much as I probably should* but also … *I guess you kinda trust them*.	*I guess I'd kind of trust that [VL] more than what we're doing.*	*I feel like I'd have to have a lot of evidence before I said* *the virtual programs wrong.*

Table 39 showing a summary of the student's belief in real and VL, together with the response to having to choose which to believe

Student	Belief in VL[1]	Belief in real practical[1]	In the event of a conflict[1]
Student A	*V+?*	*R-*	R+?
Student B	*V+*	*R+?*	*R+?*
Student C	*V++*	*R+*	*R+?*
Student D	*V++*	*R??*	??
Student E	*V+*	*R+*	*V+*
Student F	*V+?*	*R-?*	*R+?*
Student G	*V+?*	*R-?*	*V+*

[1] This is coded as + belief, ++ greater belief, - mistrust, ? uncertain, ?? very uncertain.

Table 39 shows the coding for students' responses to questions about belief in the real and VL. This is an attempt to summarise what are often complex responses to give something of an overall picture. The coding is an approximate summary of Table 38, which is in itself a summary of the students' responses in the interviews. There is, therefore, a considerable degree of abstraction involved, and the coding only provides bald headlines. Having said that, there does seem to be an initial belief in both the VL and the real laboratory, which is what might be expected. For students, both laboratories point towards the truth. The confidence in the VL appears to be greater than that for the real laboratory; this lower confidence seems to be due more to students concerns about their own abilities, rather than the effectiveness of the real laboratory to give a true result. The final column shows an estimation of the students' final position in the event of a serious conflict between the results of the two laboratories (cf. **HSW6** … resolve conflicting evidence). The process to get there is more straight forward for some students than others and is reminiscent of Gestalt switches between positions. This is shown in the changing positions students have in the responses recorded in section T5 of Chapter 4 (Appendix 12).

Table 40 showing the A level grades and marks, together with the confidence levels in VL. Also shown are the rankings for the data.

Student	A level mark	A level grade	Mark ranking	Confidence	Confidence ranking
Student A	72	E	4	R+?	5.5
Student B	112	D	3	R+?	5.5
Student C	17	U	7	R+?	5.5
Student D	67	E	5	??	3
Student E	231	A	1	V+	1.5
Student F	29	U	6	R+?	5.5
Student G	159	B	2	V+	1.5

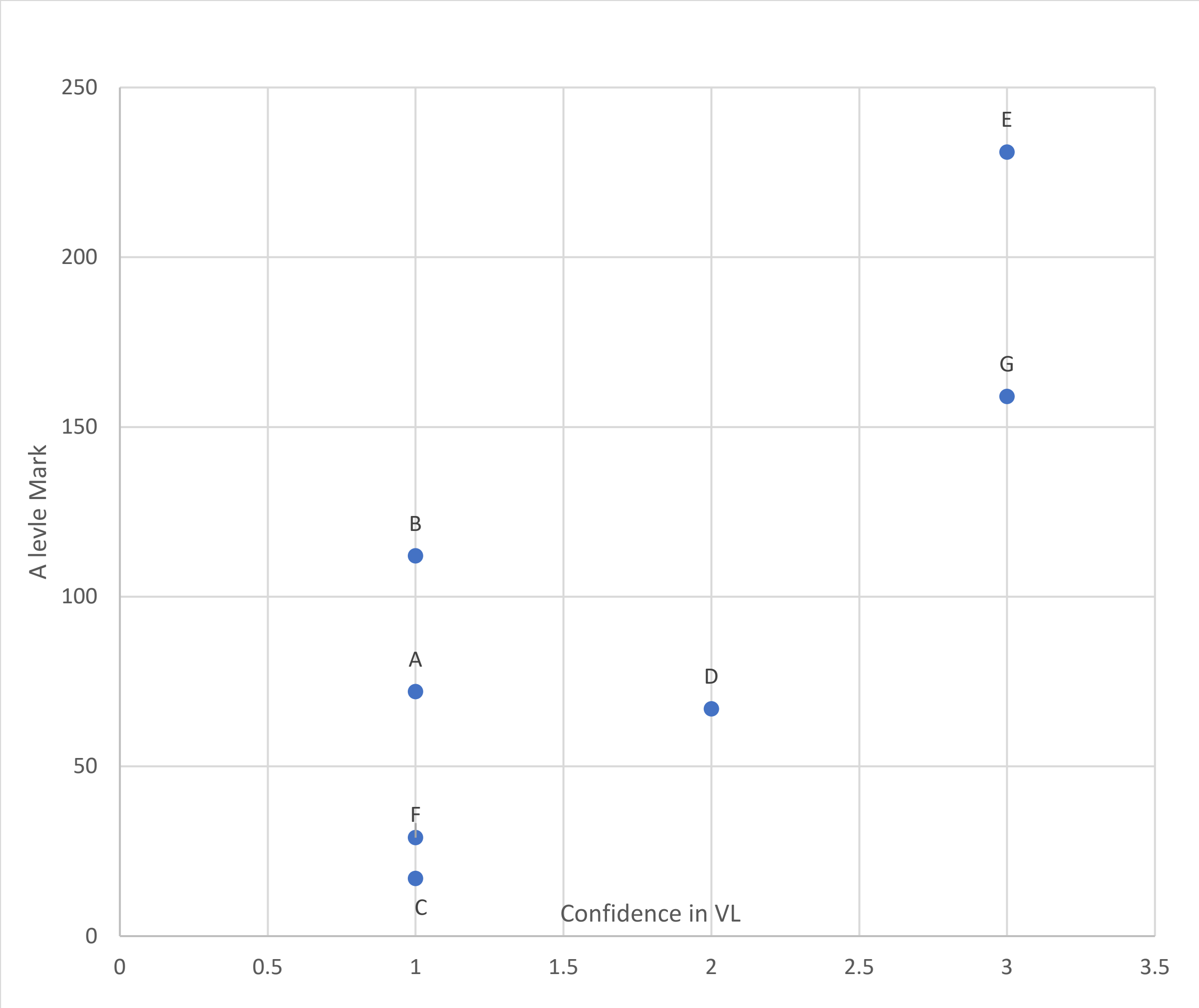

Figure 30 showing the correlation between the mark achieved in the A level chemistry exam in 2023 and the students' confidence in VL

(1 = less confident, 2 = equal, 3 = more confident). See text for more details.

This potential Gestalt switch makes Student G think, '*it's making me question',* while for Student D *'it's a bit a bit complicated …you can be in between'.* The comments of most of the students show a switch between belief in the VL, then the real and maybe back again. While the Gestalt switch is explicitly made by Student E: '*which one do you believe? Good question – the virtual laboratory … contrary to what I said'.*

An interesting observation is that the students who end up showing the most confidence in the VL (Students E and G) were those who obtained high grades at A level (A and B, respectively); while those unsure or favouring the real result obtained lower grades or were ungraded. (In fact, Student C, who expressed the greatest confidence in the real laboratory, 70 %, gained the lowest A level mark). This relationship is shown in Figure 30 where the raw A level mark for each student is plotted against their confidence in the VL. The Spearman rank correlation coefficient for the data shown in Table 40, is 0.79, suggesting a significant link between gaining good grades and accepting the theoretical paradigm (embodied in the VL). This point is supported by Holman's (2017, p. 20) observation that, 'performance in science tests does not correlate with practical science, but science epistemic beliefs and interest in science do. Practical science may not be the most efficient way to prepare for written tests'. Similarly, Ofsted (2021) state 'that it should **not** be assumed that pupils will acquire abstract, and often counterintuitive, ideas simply by taking part in a practical activity'.

Due to the small sample size and the untested methodology, no definite conclusion can be drawn from this correlation data, however, this does suggest an area for further study. What I do think is demonstrated by this data and the general tone of the interviews, is that students tend initially to believe in both the real and VL. The evidence from the surveys and interviews shows that students feel in '*the practical one … you see all the process in front of your eyes',* while 'in a virtual lab, most things turn out as they should'. This is what students are taught that theory and practice are in agreement; for subjects such as A level chemistry: the matter is settled, there is an accepted paradigm, set out in a specification (OCR, 2021). As Kuhn (1996) points out science education is different to many other subjects – it is textbook based; other subjects work with conflicting texts. Scientists are taught to accept the paradigm; teachers talk of the – '*correct answer*'; '*right for OCR'* or '*ridiculous results'* (anomalies to be ignored). Scientists follow normal science – accept theories, build knowledge within a paradigm; this is not necessarily the case for humanities subjects, c.f. Shulman's (2005) signature training for law – debate (conflicting views); medicine – ward round (words of the expert).

Theoretical perspectives

In science there is tension between practice-empiricism and theory-paradigm. 'Seeing that' and 'seeing as', Hanson (1962) talks of – theory laden observation where both are linked; Dewey denies this dichotomy. For Kuhn the paradigm is built and nurtured; for Popper the paradigm is attacked and tested. Lakatos (1984, p. 93) commenting on Popper observes, '*Belief* may be a regrettably unavoidable biological weakness to be kept under the control of criticism: but *commitment* is for Popper an outright crime'. Ideally, the VL should provide a bridge between theory and practice. Giving the flip side to theory laden observations – theory generated observations. A strong interpretation of Kuhn would be that the two paradigms are incommensurate. The VL is based on a set of theoretical assumptions; the real laboratory on empirical observation. If this is the case, and VL and real are different paradigms – then the VL would say nothing. However, if our students can hold both at the same time then there can be a dialogue between them on the common ground, this is where learning can occur.

Returning to Putnam's (1981) ideas of schema we can set up two:-

For the VL:

Schema IV(a)

Theory A

<u>Auxiliary Statements: S_{1a}, S_{2a}… etc.</u>

Observations A

For the real laboratory:

Schema IV(b)

Theory B

<u>Auxiliary Statements: S_{1b}, S_{2b}… etc.</u>

Observations B

For a Gestalt switch to occur the data stays the same, and only the interpretation changes. Therefore, the AS cannot change either, as they must exist for both potential observations simultaneously. Consequently, for a given set of data and associated AS we have a direct relationship – if we apply Theory A we see Observation A and if we apply Theory B we see Observation B. For the VL to be useful then Observations A must equal Observations B; this will not be generally true, but we can choose a subset of observations where this is the case. Similarly, for the VL and real laboratory the AS must be different in general. However, for the VL to be a useful tool we need a simplified set of AS which are true in both contexts. So, we need to identify the overlap between the two paradigms – this is where useful learning in the VL can occur (illustrated in Figure 31).

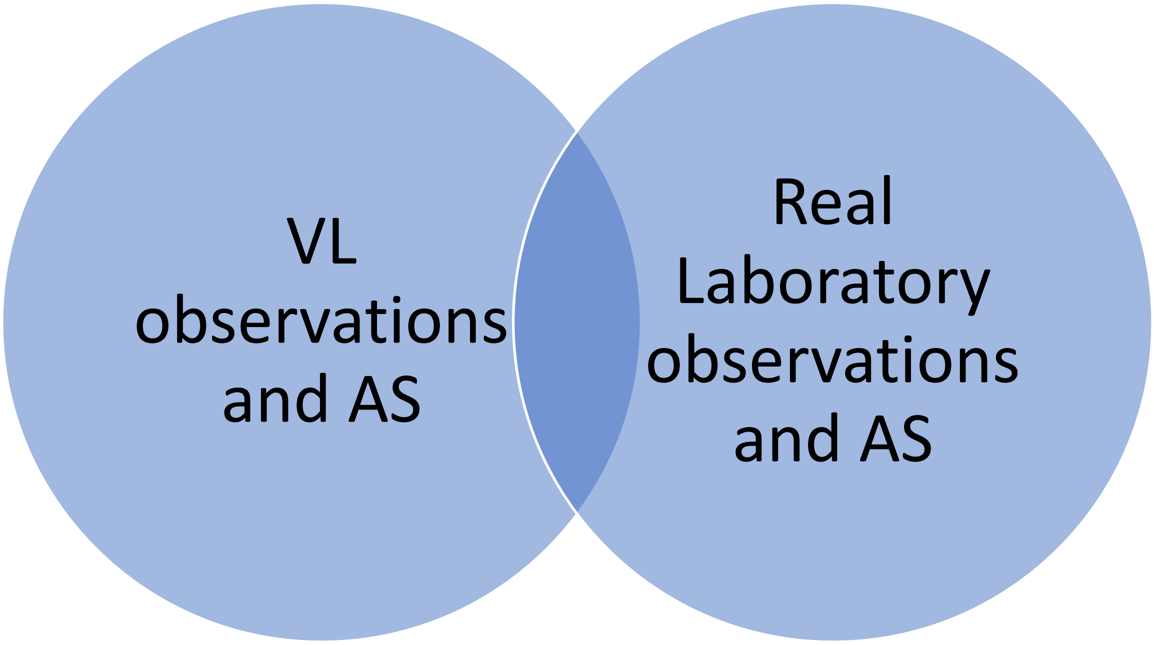

Figure 31 showing a Venn diagram of the useful zone of overlap between real and VL.

This model can be extended by considering the type of knowledge generated. In the VL knowledge is *given to* the student, whereas in the real laboratory the knowledge is *generated by* the student. The implicit structure of the VL will tend to produce patterns which are more easily transferred into knowledge than the confusing mele which is the real laboratory. Since the observations and the theory are linked for the VL – they are aligned – learning will be more straightforward. In a sense, the pattern of the theory is superimposed on the observations which are made. This is not the case real laboratory where any patterns are often obscured by the quantity of data. If we can work in the area of overlap, using the VL patterns to prime and reinforce those observed in the real laboratory, we have the opportunity for deeper learning. Using the language of patterns, we want to use the VL to establish a set of explicit or tacit patterns which will provide a framework against which experiences in the real laboratory can be measured. The VL is well suited to this task, providing a '*step by step how to do it'* and allow them to *'physically see the theory behind an experiment'.*

An alternative conceptualisation is inspired by Brandon's Matrix which has been discussed earlier. This can be reconfigured as a two-by-two matrix with axes expressing belief in the two laboratories, this is shown in Figure 32. The data generated in Table 39 can now be added into this matrix, to provide summaries of the initial and final beliefs, these are shown in Figure 33 and Figure 34, respectively.

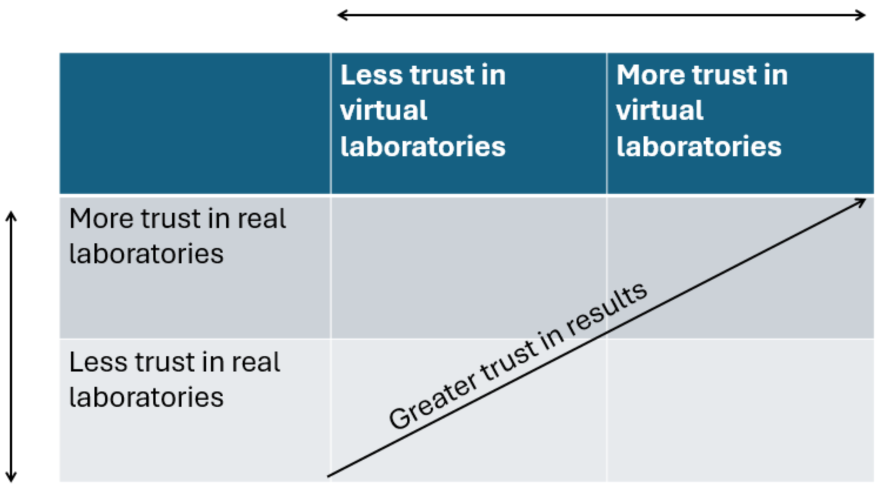

Figure 32 showing the two-by-two matrix of trust in both real and VL.

	Less trust in virtual laboratories	More trust in virtual laboratories
More trust in real laboratories	0	7
Less trust in real laboratories	0	0

Figure 33 showing the initial level of student trust as a two-by-two matrix for both real and VL.

	Less trust in virtual laboratories	More trust in virtual laboratories
More trust in real laboratories	4	0
Less trust in real laboratories	1	2

Figure 34 showing the final level of student trust, as a two-by-two matrix, for both real and VL.

These matrices represent the transformation of students ideas by the questioning about belief in the case of a conflict between the results of real and VL. The change caused by this process appears to be two-fold, a reduction in the belief in the real laboratory and/or a reduction in the belief in the VL. So, we could represent this by two separate processes, Q_{RL}, causing a reduction in the belief in the real laboratory and Q_{VL}, causing a reduction in the belief in the virtual laboratory. Thus for Figure 32 to Figure 34, if the matrices are of the form

$$\begin{matrix} a & b \\ c & d \end{matrix}$$

Q_{VL}: $b \rightarrow a$; Q_{VL}: $d \rightarrow c$; Q_{VL}: $a \rightarrow c$; Q_{VL}: $b \rightarrow d$. So, we can potentially identify individual changes in belief as a result of such questioning. This type of analysis might prove fruitful in exploring beliefs further but is beyond the scope of this work.

Summary

Truth is a difficult concept which Kuhn (1996, p. 172) suggests emerges through a Darwinian process '*from* primitive beginnings but *toward* no goal'. He continues that science develops 'without benefit of a set goal, a permanent fixed scientific truth' (ibid., p. 173). For Kuhn science is a process, we are solving puzzles within the paradigm of normal science. This is also the experience of the students who are also learning to solve puzzles, set by the examiner within the 'paradigm' of A level science. 'Truth' for our students is defined by the A level syllabus. This truth is derived from 'How science works' and the scientific 'community's paradigms, revealed in its textbooks, lectures, and laboratory exercises' (ibid., p. 43). These are propagated through 'the authority of teacher and text' (ibid, p. 80).

Students are taught to accept the *truth* of the scientific paradigm, as their teachers were taught before them. This truth is enshrined in the accepted theories, and it is these theories which are embodied into the VLs. Teachers check that the VL matches the requirements of the specification and are '*right for OCR'.* Teachers and students both accept the VL as truthful because of the authority of '*reputable universities or companies*' and feel '*a scientist, [would] always wanna get the best end result'.* For students this belief in the VL is further enhanced by the authority of the teacher *'if my teacher directed me to it, then I believe the teacher to be right'.*

However, there is a second paradigm which the students are taught to accept that of empirical evidence; that 'observation is just opening one's eyes and looking. Facts are simply the things that happen; hard, sheer, plain and unvarnished' (Hanson, 1962, p. 31). This is the basis of the 'scientific method' of presuppositionless observation discussed in Chapters 2 and 3. Students believe the results when they are *'seeing things in my own eyes'.* Even though there is the combined authority of teacher and exam board, students are still prepared to question based on the evidence of '*their own eyes'.* There exists a tension between these two sources of authority which validate the students' experience.

However, we can carry out a thought experiment – what if the results of the real and VL are different? For Kuhn (1996, p. 170) 'truth and falsity are uniquely and unequivocally determined by the confrontation of statement with fact'. This is the case here, the VL is a statement of theory – the paradigm; the fact – an experiment result. Which do students choose? Unsurprisingly, there are a range of answers, which are not entirely clear. However, what seems to emerge is that those students who have greater belief in the VL (theory) go on to achieve better grades than those who favour the real laboratory. Perhaps this is not as surprising as it first seems, the VL is the accepted paradigm, embodied theory; while the real laboratory is many things in which the 'paradigmatic truth' is lost in the confusion of reality. In a sense we can regard the truth the learner finds in the real laboratory as one *constructed* by the student themselves from their experiences and implicit or tacit knowledge; whilst the VL offers a truth which is *instructed* (imposed) externally though the authority of explicit knowledge.

RQ3: The extent to which teachers can have confidence in the educational value of learning in the virtual laboratory?

Education for Carr (1995, p. x) is the 'the process through which people acquire that kind of philosophical enlightenment that will emancipate them from the dictates of ignorance, dogma and superstition'. Generally, for our students the aim is more mundane – to achieve their qualification so they can progress in life. This follows the idea of constructive alignment which gives 'a framework, anchoring teaching decisions all the time to aiding students in achieving the intended learning outcomes and assessing how well they do so' (Biggs and Tang, 2011, p. xx). As teachers we often sit between the two, aiming for one but knowing we will be assessed by the other.

In this section the research question, RQ3, is addressed through three different lenses. The first is that of the thought experiment as a model of VL and Kuhn's (1981) reflections on a study by Piaget. This illustrates the potential for conceptual development. The second is Schulman's (2005) studies of signature pedagogies, addressing the value of practical science and the VL within this model. The third is a more general exploration of the VL as a tool for teaching in different contexts.

VL as a thought experiment

Kuhn (1981) has considered the use of thought experiments as a way to change concepts. He looks at this as an educational process, using Piaget's experimental work with children, concerning the idea of speed. The thought experiment has been an integral part of science for centuries; imagining experiments which may or may not be physically possible (Kuhn, 1981, p. 6). The VL is in a sense an embodiment of a thought experiment; one which has been externalised. The VL provides a framework and structure to the thought experiment which may not otherwise exist. Kuhn (ibid, p. 7) suggests three questions should be asked about these experiments; these are also relevant to the consideration of VLs:

i) 'To what conditions of verisimilitude is it subject? … must the situation be one that nature could present…?' (c.f. RQ1)
ii) 'How, relying exclusively upon familiar data, can a thought experiment lead to new knowledge or to new understanding of nature?' (c.f. RQ2, 3)
iii) 'What sort of new knowledge or understanding can be so produced?' (c.f. RQ3)

Although, in an FE setting we are not looking to produce 'new knowledge' in absolute terms, for each of our students, we are hoping they will gain a 'new knowledge [and] understanding of nature' (ibid, p. 7). Kuhn says, like the VL, this 'must rest entirely on information already to hand' (ibid. p. 24).

Kuhn suggests that the historical view of thought experiments is that they should produce a new understanding of the participant's '*conceptual apparatus'* and 'the elimination of confusion'. He suggests the only condition required for this to be possible is verisimilitude. In our case, this means that the students just need to believe in the apparent truth of the VL, which in general they seem to do (see Table 38). Under these circumstances, learning in the VL should help 'the elimination of existing confusion' (ibid., p. 7). However, Kuhn extends this model, based on analysis of experiments carried out by Piaget and Galileo. Piaget studied how children develop the concept of speed based on the movement of toy cars. He explored the idea of average speed, total time and total distance; and the paradoxes which arise from these different ways of judging speed. Kuhn (ibid, p. 10) says that 'the mental apparatus which Piaget's children brought to his laboratory contain an implicit contradiction' between 'something like the adults' notion of 'faster' and a separate concept of 'reaching-goal-first'';

as a result, some of them changed their concept of 'faster'. Kuhn then describes conditions almost identical to the VL and states – 'Presented with an animated cartoon showing the paradoxical motions, the child would reach the same conclusions about his concepts, even though nature itself were governed by the law that faster bodies always reach the goal first. There is, then, no condition of physical verisimilitude' (ibid., p. 11). That is, that Kuhn is saying that the model does not need to be a true physical representation, only that it includes the 'normal clues' required to make 'judgements of relative speed' (ibid., p. 10). Applying these ideas to the VL, we can see that Kuhn, would regard a simplistic VL as adequate, if it provides 'normal clues'. This is the case for the RSC screen experiments which show the simplified structure of a titration experiment but appears to contain all the 'normal clues' for such an experiment. Teacher S believes that when *'we did a virtual lab … they can see that it is representing what we do in the lab, and I think they have no trouble with that concept as far as I'm aware'.* While, for Student E – *'I'd say they're quite similar, cause you're still thinking about the reaction, you're still thinking about the same process that you know, or that you don't know if it's a new reaction'.*

Kuhn then considers the work of Piaget in the light of the ideas of Aristotle and Galileo, developed through their thought experiments. He concludes that if the thought experiment shows 'a misfit between traditional conceptual apparatus and nature, the imagined situation must allow the scientist to use his usual concepts … it must not … strain normal usage' (ibid, p. 27). For our students this would mean that the ideas presented in the VL, should not be unduly novel but fit with previous understanding, even if it emphasises inconstancies. Kuhn now proposes a second condition for the thought experiment, that 'the conflict deduced from it must be one that nature itself could present' (ibid, p. 27). That is, for the thought experiment and by extension the VL, to resolve a conflict, it must have more than verisimilitude, it must relate to an 'experimental situation … that, however unclearly seen, has confronted him before' (ibid, p. 27). This will be the case for our students who have experienced titrations before engaging in the VL.

However, perhaps a VL, such as that from the RSC, is too prescriptive to function effectively as a thought experiment; not allowing enough latitude in thought. The RSC titration experiment focuses on developing method within a defined scenario, whereas others, (e.g. Beyond Labz (2024)) allow more options to explore concepts independently. These may allow students to imagine other situations to resolve any 'misfit [of their] conceptual apparatus and nature'.

Practical science as a signature pedagogy

Kuhn (1996, p. 47) describes a 'process of professional initiation. As the student proceeds from his freshman course to and through his doctoral dissertation, the problems assigned to him become more complex and less completely precedented. But they continue to be closely modelled on previous achievements'. He also suggests that 'accepted examples of actual scientific practice—examples which include law, theory, application, and instrumentation together— provide models from which spring particular coherent traditions of scientific research' (ibid. p. 43). This similar to the ideas of Shulman (2005) who, as discussed in Chapter 2, identifies three dimensions to signature pedagogies. These are now explored, in turn, in the light of student and teacher responses.

Surface structure

Firstly, Shulman talks of '**a surface structure**, which consists of concrete, operational acts of teaching and learning, of showing and demonstrating, of questioning and answering, of interacting and with holding, of approaching and withdrawing' (Shulman, 2005).

The students identify a ritualistic quality to practical science, the wearing of special clothes: *'like in year 11, you think I'm gonna wear a lab coat and I'm gonna do all these practicals', 'the goggles and the lab coat'* it is *'a uniform'* and then I *'tie me hair up'.* This gives the student the feeling of *'authority*', they say *'I'm putting on this lab coat, people around me are gonna think I know what I'm doing'* this gives confidence*, 'so let's make it look like I know what I'm doing. Let's do it right. Let's do it. Let's get the results I want'.* The students feel this an outward sign, a '*stereotype – the goggles and the lab coat',* when *'you put it on', you* feel you can say *'I am a scientist'.* Then, they recall the performance of certain acts, Dewey's (2011, p. 122) 'ritual of laboratory instruction' – *'light[ing] the Bunsen burner'* then *'doing things … carefully and accurately … measuring something … having to repeat a process … put[ting] the data in a graph',* identifying *'hazards',* measuring the *'end pointing of the acid and the base',* using *'your hands to process the experiments'* and *'follow instructions… tick it off … being more organized, making sure your equipment's in the right area'* then *'follow the steps and do it as accurately as I can, so I can get the right result'.* These things are part of what the students see as being a *scientist*. There are certain types of experiments which seem an essential part of the canon for chemistry – *'I think for me it was like titrations … but I think even at like GCSE, you talk about titrations, I'm pretty sure like I could ask my dad who has no science knowledge to talk about a science experiment and you'd be able to say the word titration'.* Chemistry teachers, '*talk about titration'* and regard 'titration and an organic synthesis' are essential practicals. For biology it is perhaps '*the dissection practicals'*, which fill this role, so essential that even though '*a lot of my students faint when they do it'*, the heart or fish dissection is still carried out in class.

However, there is a different experience in the VL, *'it's more you're seeing it happen, but I don't think you're learning it yourself … with like multitasking and being organized and stuff, there's not really any way to do that over a virtual lab. It kind of goes through in the most like, efficient way …. It tells you what to do, as you're doing it. So, I feel like you don't have to apply as much to it'.* Similarly*, 'sometimes it kind of like does it for you. So, you [are] kind of just sitting there and watch[ing]'.* Students do not feel they are participants in the rite. Similarly, for some practicals teachers feel that sometimes *'there's no way you'd be able to learn that online … dissect a heart using your knowledge from all that you've learned online, I just don't think it would work … the different textures of the … things you're dissecting for, the different way you're gonna feel when you're dissecting something like that'*.

Deep structure

Shulman also claims there is '**a deep structure**, a set of assumptions about how best to impart a certain body of knowledge and know-how' (Shulman, 2005).

Practical science has a number of facets, as described by Holman (2017) and these can be seen as part of Shulman's deep structure. There is an ethos of practical experience which, students say, 'doing the actual thing myself helps more' and 'you learn more by experiencing it yourself'. They feel that 'it lets me remember what I do and the steps better' and 'hands on experience and being able to interact with the experiment helps you understand better'; also, they '*would say you do think about the process you experience in your mind'.*

However, some teachers might question this deep structure – *'You know, actually, we can all do the process of a titration. You could teach someone to do a titration and … get the correct figures, get the end point, put the numbers into a calculation, but actually understanding what's happening, why does it need to be multiplied by two, divided by two? Why does it react like that – I'm not sure'.* Similarly, Kuhn (1996, p. 47) sees little evidence for such a deep structure, he says 'One is at liberty to suppose that somewhere along the way the scientist has intuitively abstracted rules of the game for himself, but there is little reason to believe it. Though many scientists talk easily and well about the particular individual hypotheses that underlie a concrete piece of current research, they are little better than laymen at characterizing the established bases of their field, its legitimate problems and methods'. For Kuhn the scientific training is focused on narrow themes within 'normal science' and is aim 'is to solve a puzzle for whose very existence the validity of the paradigm must be assumed' (ibid. p. 80).

There must be a recognition that there is more to learning than being taught. Students must engage at some level with the activity beyond the purely physical – simply going through the motions. This is recognised by one student who sees how learning occurs in the VL, the difference between being taught to do and learning to understand – '*You experience doing the same motion pouring the substance, but there is a difference between doing it in real life and doing it [virtually], you don't really use the same skills. You don't practice the skills that you use in real life… it's mainly the manual dexterity part of it, you don't practice that…You do still practice your problem-solving skills though. So that's, quite similar, you still have to go through the motions and do the processes… I'd say the theoretical part is still there'.* Others also see this separation of practical and theoretical learning in the VL, so while they 'only properly learn about physical components in an experiment if I do them in a physical lab'; they find 'virtual labs are more helpful in terms of theory work'. Also, the 'virtual laboratory focuses more on the method rather than skill' *and 'more in terms of understanding the practical and just going through it in order to get it'* which 'decreases the probability of error and is a[n] accurate demonstration'. As one student puts it '*the virtual laboratory is easier in terms of understanding things – mathematically. The physical laboratory is easier in terms of understanding how things actually work'*. However, some students feel that 'hands on experience and being able to interact with the experiment helps you understand better' or that they gain 'more understanding in physical laboratories as it helps to see what I am doing properly'. So, VL is providing some but not all of the deep structure of the 'signature pedagogy' of practical science.

The VL is based on a set of rules and assumptions which create its deep structure. These are programmed into the VL and can be viewed as the theoretical framework. Built on this is a form of pedagogy which is intended to reveal this structure. There is a logical progression through activities, each of which must be completed before the next. The chances of error or misdirection, at least for VLs such as the RSC screen experiments, is minimised and a definite path is set out. This contrasts with the real laboratory where the deep structure is given by a multitude of interactions, which do not always align with the intended framework. Although there is a pedagogical structure, provided by the method sheet, students are able to (and do) deviate from this. The structure is more fluid and provides more a direction of flow, rather than a fixed route. This allows for the possibility of enquiry as proposed by Dewey (see Chapters 2 and 3), which is interactive, allowing the student to modify the reality they experience.

Implicit structure

Then below the other structures, Shulman suggests, there lies an '**implicit structure**, a moral dimension that comprises a set of beliefs about professional attitudes, values, and dispositions' (Shulman, 2005).

Students tend to implicitly *'believe in scientific credibility especially if it's something …tangible ... it's something … you've seen'.* They trust *'people who kind of been in the industry … They know what they're doing'.* '*I think … if it's … around science … what reason do they have for it to not be right? …, they have no reason to put wrong information in there. It wouldn't benefit them, and it wouldn't benefit us … I think actually, I would trust them because why would they do it wrong?'.* There is an underling assumption that when developing a VL, *'Researchers go into it'* and *'that there's a lot of background research. It's been like peer reviewed; people have tested it'.* While teachers trust of the VL also relies on *'reputable universities or companies … that they have done their research and they've got everything right'.*

Moreover, students find that *'having the practical side of ... it makes it feel more real'.* In fact it is for them an integral part of science education: *'it's like if you ask a chef to learn to be a chef without cooking … because science is so hands-on'* or *'like doing your driving theory test doesn't mean you can drive', and even though 'you could explain the whole of chemistry, but … you can't do it'* – *'Would you actually be a scientist?'*. For these students, practical experiments are an essential feature of science, they do not see science without the practical element, it is an implicit part of being a scientist. This is confirmed for them by the HSW agenda (see Chapter 2; especially HSW 4-6, 11) and the Common Practical Assessment Criteria (CPAC) requirements of the A level specifications (OCR, 2021) – it is part of the accepted landscape – the paradigm. This point is also brought out by Kuhn who says ''normal science' [is] firmly based upon one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice' (Kuhn, 1996, p. 10). We work within 'a set of recurrent and quasi-standard illustrations of various theories in their conceptual, observational, and instrumental applications. These are the community's paradigms, revealed in its textbooks, lectures, and laboratory exercises. By studying them and by practicing with them, the members of the corresponding community learn their trade' (ibid, p. 43).

There is however a difference in the implicit structure of the real and VL, while both fit within the paradigm of 'normal science' their underlying logic is different. The VL is firmly based on logic with causality written into its structure. However, the basis for experimental science is a point of discussion with some of the views discussed in Chapters 2 and 3. While, there does not seem to be a consensus, few of the authors considered would support the fully inductive paradigm of explicit causality. This means that some of the implicit assumptions at the level of the student's tacit knowledge will be different. This is expressed in some sense by the teacher's comment that '*I think the students probably regard the … virtual labs as kind of like a best-case scenario result – Not very realistic, but still fairly reliable, if that makes sense'.* The VL results, then are fitting into what is expected – *'because it's a computer … it's gonna tell me the right answer'* – fitting into the logic of the computer program; however, in the real laboratory '*the results are never quite what you expect. They can see that they're collecting … real data … why was that data not perfect … what variables can we not control in biology … things that could be affecting the results today … they see that biology is real and tangible … Through the … sometimes untrustworthiness of the results'.* This is the point made by Cartwright, (quoted in O'Hear, 1990, pp. 128-129) that 'in general, nature does not prepare situations to fit the kinds of mathematical models we hanker for'. Similarly, teachers recognise that there are different levels of learning which are addressed in different ways between the laboratories, asked about the value of VL one replies '*… Do I think they gain more... understanding of the theory? … I think it's possibly more memorable, but … that's not necessarily understanding, is it? Understanding is something more intricate. I don't know [what] is the truthful answer … about the true understanding'.*

Summary

It might be possible to summarise this discussion by suggesting that *practical science* displays the characteristics of a signature pedagogy. While, the VL demonstrates a different pedagogy, which while meeting Shulman's (2005) criteria in other ways is missing a key element. To me the distinctive nature of a signature pedagogy – is the emotional engagement of the participants. In Shulman's (2005) examples of the ward round and case dialogue, there is an element of theatre, participating in a role. This is something students find in practical science which is missing in the VL.

VL as a teaching tool

Buckminster Fuller (2017) suggests that 'If you want to teach people a new way of thinking, don't bother trying to teach them. Instead, give them a tool, the use of which will lead to new ways of thinking': the VL can provide just such a tool. The teachers interviewed both were both positive about certain aspects of VL. They *'… add, to teaching practice, to learning …, independent and any time … the virtual labs will add to that, and students can do it at their convenience'* and *'… because they are taking in information and reinterpreting it into some questions and answers. They're also learning alone a lot of the time, so it's independent learning; which is good, good skill for university'.* There is also a good deal of positive comments in the RQ3 section of the Phase 3 survey results reported in Chapter 4 and Appendix 14 and students' views about their own learning recorded in Phases 1 and 2 of Chapter 4. This section focuses on the positive contribution that VL can make to teaching and learning. In agreement with the findings of Zacharia (2003) most teachers feel that VL is best used in combination with real laboratories. The main themes which have emerged and are discussed in this work are the VL:- as a way to learn and practice certain skills; as an aid to understanding theory and abstract concepts; used to aid anxious and neurodivergent students; used to develop independent learning skills; to provide assessment and to provide a revision resource. Each of these will be briefly examined in the light of staff and student responses and the relevant literature.

Skills

Sennett (2009) considers the relationship between a craftsman and their ability to describe their work, in a similar way to tacit knowledge, he suggests 'craftwork establishes a realm of skill and knowledge perhaps beyond human verbal capacities to explain' (ibid., p. 95). A similar idea about skills is expressed by one of the students *'you cannot imagine them or … think about them unless you do it in practical ... Otherwise, [if] you want to learn them, you don't know the reasons of it'.* However, there are number of skills which can be described explicitly. Teachers and students themselves have identified a number of specific skills developed both real and VL, these are shown in Table 41. It can be seen that not all these skills are present in both laboratories. Generally, the missing skills correspond to the interactions described previously (c.f. RQ1).

Table 41 showing the reported skills developed in the real and VL

Skill	Real laboratory	VL
measurement	*how to take exact measure from pipette or use dropper*	*you could get that kind of skill and knowing*
teamwork	*you actually learn teamwork skills*	*you're not talking to anyone or helping people out.*
Social	*the social skills you need to be able to use equipment*	
communication	*on the spot, problem solving and quick thinking and, and teamwork and communication, it all comes together into one cohesive learning experience*	*if they're reading and having to interpret information, and if there's follow up questions*
manipulation	*how to use your hands to process the experiments,* *the fiddly things that you're doing with the equipment.* *fine tuning the fine motor skills*	*manipulate molecules on the computer program and like measure things … on the DNA molecule.* *mainly the manual dexterity part of it – you don't practice that*
working carefully	*doing things more carefully and accurately*	*step by step how to do it*
following instructions	*follow instructions… tick it off*	*kind of guides you through it*
planning	*the step-by-step plan*	
problem solving	*on the spot problem solving and quick thinking*	*still practice your problem-solving skills*
evaluation	*they can evaluate improvements for a practical*	*evaluation, you can do virtually*
health and safety	*it teaches people health and safety*	*well, that's not, that's not bothering me*
multitasking	*multitasking skills*	
skills for life	*something that's quite transferable*	*you don't really use the same skills; you don't practice these skills that you use in real life*
splitting duties	*splitting of duties*	
spatial awareness	*tons of other people in there as well, so you've got to be careful*	

Sennett (2009, p. 52) says 'skill is a trained practice'; for him a skill is developed over time through 'repetitive, concrete, hands-on training' (ibid). He fears that 'modern technology … deprives its users precisely of that' repetition by which skills are honed. Sennett goes further and says, 'the head and the hand are separated, the result is mental impairment' (ibid). For the students in the real laboratory, you are *'touching stuff, like it is all connected to your brain. So, it kinda triggers like, oh, I know what that is – type of thing. Where if you just touching, like, just the keyboard, then it's just like – that's all';* so, they are '*just scrolling mindlessly and clicking mindlessly in a virtual lab'.*

So, although it is possible to develop some skills in the VL, these are more limited than in the real laboratory, in particular it is more difficult to develop those where interaction is important. It is still possible to develop higher level problem solving and evaluation skills.

Concepts and Education

Dewey (2011, p. 122) describes science education as too often 'learned in [a] condition [where] it remains a body of inert information'. He continues that 'Contact with things and laboratory exercises, while a great improvement upon textbooks' are not always educationally successful; 'our attention may be devoted to getting skill in technical manipulation without reference to the … subject matter' (ibid, p. 122). The VL allows us to move beyond the nuts and bolts, to see more of the picture, without the distractions of the '*different kinds of stimuli hitting you at once',* while trying to learn the '*skill … to take exact measure from pipette or use dropper and all these things'.* This is part of the advantage of VL seen by Teacher T '*… abstraction – I think it is that; at the minute we can use virtual laboratories, we can see things that we couldn't see before… we are moving on with that kind of abstract ideas'*; so*,* 'the student become an inhabitant of the scientist's world, seeing what the scientist sees and responding as the scientist does' (Kuhn, 1996, p. 111). Dewey (2011, p. 122) says that 'scientific statements … implies the use of signs or symbols …designed, … not to stand for things directly in their practical use in experience, but for things placed in a cognitive system …Atoms, molecules, chemical formulae … all these have primarily an intellectual value and only indirectly an empirical value'. Dewey (ibid, p. 122) continues this idea of scientific abstraction 'Even the circle, square, etc., of geometry exhibit a difference from the squares and circles of familiar acquaintance, and the further one proceeds in mathematical science the greater the remoteness from the everyday empirical thing'.

These ideas suggest that abstract nature of some VL is not a problem but an advantage. Scientific thought is not as that of the everyday, but where 'direct physical quantities have been transmuted into tools for a special end – the end of intellectual organization' (ibid, p. 123). Thus, for Dewey, the abstract VL, with lines on a screen standing for laboratory equipment, and laboratory equipment standing for molecular interactions, and molecular interactions expressed as symbols on a page, has a kind of circularity. There is a sense in which the VL is 'pure science' not cluttered by the day-to-day glassware and washing-up. This reduces the cognitive load, by excluding non-essential material and focusing on essential (abstract) features (Rau, 2020). Similarly, for Kuhn's (1981) thought experiments, it is the ideas – the theory, which separates science from the mundane. Deming (1994, p. 103) goes further and says 'Experience by itself teaches nothing…Without theory, experience has no meaning. Without theory, one has no questions to ask. Hence without theory there is no learning.'

Another area where the VL provides an advantage is through the natural scaffolding of tasks which is achieved in the VL. Due to the structured nature of a VL it is simple to introduce step-by-step instructions when appropriate. Assessment for learning tasks or quizzes can be used to judge how comprehensiveness any help provided needs to be. These types of activity can be naturally embedded in the structure of the VL.

Anxiety and Neurodivergence

Sennett (2009, p. 96) states that 'trial and error was a guiding method of experiment' for scientists, over many years; with the principle ''Bad results' will cause people to reason harder, and so improve' (ibid, p. 96). Our students have echoed this by saying in the real laboratory '*I've put the wrong chemical in – I've got to start again',* but in the VL *'you did it wrong a few times … it would take you the right way the next time'* so *'I think you don't actually learn from your mistakes … whereas in a normal lab you'd have to start all again…'.* However, Sennett cautions 'learning by doing, so comforting a nostrum in progressive education, may in fact be a recipe for cruelty' (ibid, pp. 96-97) for those whose confidence or 'talents prove insufficient' (ibid, p. 96). He extends this idea to the concept of agency, placed at 'the intersection of practice and talent' (ibid, 97), saying that 'the desire to do something well is a personal litmus test; inadequate personal performance hurts' (ibid, p. 97). Teachers also recognise these points and the advantage provided by the VL, which is 'especially beneficial to learners who feel initially anxious about physical practicals', and also 'for weaker or neuro-divergent students who cannot grasp new concepts as quickly'. Also, the real laboratory can be a stressful place, when *'there's tons of other people in there as well, so you've got to be careful about being with around other people, making sure everyone else knows what's going on'* and for some experiments, such as *'when you're dissecting something ... a lot of my students faint when they do it'.* So, the VL can provide a safety-net for some of our students.

Independent Learning

The VL provides an opportunity for independent learning which is not available in other ways. It is not logistically possible to provide practical science on-demand; yet for the VL students can '*just quickly hop on a computer or your phone, carry it out, and then it's back in your head'.* Teacher S suggests that *'they're also learning alone a lot of the time, so it's independent learning, which is [a] good skill for university'.* As with other forms of independent learning, the success often depends on the motivation of the students. Teacher S says*, 'really good independent learners could go away, use all that information, write it down into neat notes, and then learn from it. Other students click through, yeah – I kind of get it and then never think about it again'; they continue by saying 'it's a good tool, but it depends how the student uses it'.* Sennett (2009, p. 197) addresses this point discussing 'the tool that works well but which people have trouble inferring how best to use'. For the teacher the solution is *'we can model in class so that … learn how to … make the best of those resources'.* However, for some tools Sennett (ibid. p. 199) says, that the 'knowledge [can be] too primitive for the master to explain', while 'the possibilities of using simple tools in many ways increase the puzzle of how they are best employed in a particular application' (ibid. p. 198). This is echoed by Teacher S*, 'they're not universal, but if used correctly, they can have pretty good learning outcomes';* students need to be helped to focus on the tasks. For Sennett (ibid. p. 177) 'learning to concentrate has to come first' because *'there's always gonna be the student that does the bare minimum and doesn't actually take on the information correctly'. '*[S]ince craftsmanship is based on slow learning and on habit' (ibid. p. 265) the VL can give that opportunity to develop knowledge and skills over time. As Teacher T points out, commenting on the inclusive nature of the VL, *'When does the learning have to take place? Does it have to be fixed?'* For the VL *'the type of learning it provides is of course, independent and any time'.* This freedom from time constraints may allow 'the pursuit of quality [through] learning how to use obsessional energy well' (ibid. p. 243) as students can learn when they are in the mood for this kind of learning. Additionally, due to the structured nature of many VLs, such as the RSC titration, for the student, '*everything is already there for you to have … a smooth practical before you do it in a lab'*.

This is useful for independent learning especially as there are *'videos to help you direct to the reaction, so that's quite helpful'* and *'there's usually, step by step how to do it'.*

Assessment

While some teachers feel, students 'learn more in a physical lab with appropriate guidance from the teacher … virtual labs can complement this well with more continuous individual feedback possible than a single teacher with a large class'. Also, a teacher suggests that for students, 'a virtual lab could … be a great tool to use before a practical assessment', which 'enables them to experiment with different situations quickly and safely'. Additionally, they feel *'some of the virtual labs, especially for the biotechnology bits and bioengineering is quite good because they can take their time with it, write notes down and one of 'em has like little multiple-choice questions at the end … for a bit of assessment for learning. So, I think for theory actually, some virtual labs are quite engaging'.*

When considering more formal assessment, Biggs and Tang (2011, p. 98) talk of using 'criterion-referenced assessment which is how anyone outside an educational institution assesses what has been learned when teaching anyone else anything'. This is how the PAG assessment is made, against the CPAC requirements (however, the A level exam itself is slightly different with the use of normalised grade boundaries). Potentially, the VL can provide an aligned system, this appears to be the case for the RSC activity, where Biggs and Tang (2011, p. 99) would say 'the students are 'entrapped' in this web of consistency, optimizing the likelihood that they will engage the appropriate learning activities'. This agrees with the feelings of Teacher S, who finds assessment of learning difficult in the complex mele of the laboratory '*… you're trying to assess things or make sure that a learner has described this, explained that evaluated this … carried out that practical, it can be difficult sometimes to be sure that every single student has met every part of that practical, like where they actually helping the whole time … have they managed to understand the point of the practical or did they just follow the instructions? … it can be difficult to measure that, I suppose, in an environment that can be confusing and there's lots going on and there's people pulling you here, there and everywhere'. 'Whereas in a virtual lab … you know … if they've been engaged the whole time, have read the information, have hopefully understood the information … if they don't, they can go back and look at the information a second time … I suppose using a virtual lab is more, is more measurable in terms of how well they've … accessed that information'.* Biggs and Tang (ibid, p. 99) suggest, '[c]onstructively aligned teaching is likely to be more effective than unaligned because there is maximum consistency throughout the system' and the VL is able to provide this consistency. The assessment is also more likely to be objective and closer to the specified learning outcomes, due to the closer focus on the assessed activities.

Revision

Students have identified the VL as '*a good way of testing what we already know…[and] … recap what you've done'.* In this way the VL *is a 'revision source in a way … So, you going through what you've already done'* however, they also feel *'it's not necessarily learning, it's necessarily recapping what you've already done'* and that *'you tend to pick up more with an actual … practical lab because it's a lot more hands on…Whereas the virtual one, I think [it] … just kind of tops up what you've already learned'.* There is a difference here between the constructivist learning in the real laboratory where students are making their own meaning though interactions and that in the VL where meaning is made for the students by the underlining theory. Even observations made in the real laboratory are theory-laden so part of the dominant paradigm. This all points towards the material which needs to be learnt and reproduced in the exam. Although the VL may not provide such a memorable experience, it can provide a purer view of the requirements for the exam.

Brandon's Matrix

In a similar fashion to that discussed above, two-by-two matrices, inspired by that of Brandon (1994) can be used to investigate the interplay between different aspects of learning. For example, the data collected in Phases 1 and 3, concerning the value of practical science can be displayed in this way. Since the data is collected on Likert scales, it is readily amenable to a matrix format. Two examples are shown here: the first, compares the interplay between for the student data (Phase 3) and the second compares data for the same parameter between phases (i.e. Student/teacher perspective).

Taking the case of students views on learning theory (QS2) and gaining higher skills (QS5) as these show the biggest differences between the laboratories shown in Table 29. These can be represented by a matrix such as shown in Figure 35. This figure suggests a greater leaning experience in the real laboratory with a correlation of greater learning of higher skills and theory. Although this may be the case for some students, when compared to the more nuanced responses from interview data, this figure illustrates that reliance on quantitative survey data can sometimes be misleading.

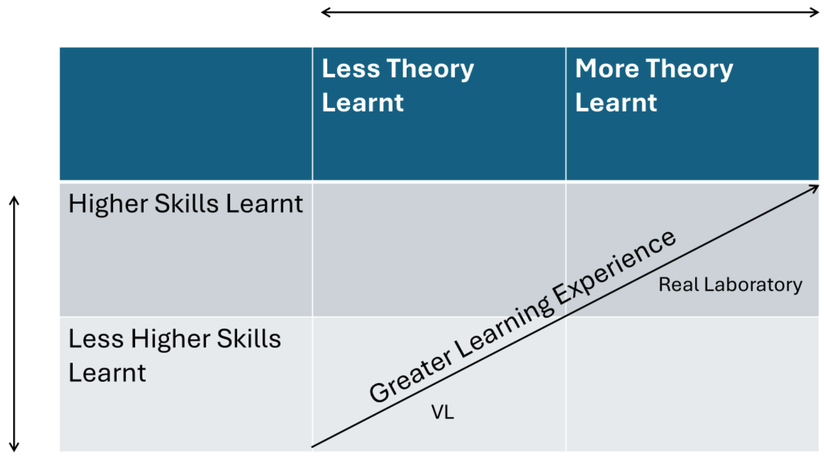

Figure 35 showing a matrix representation of the reported learning experience of students in real and VL, from survey data.

A similar process of comparison can be illustrated for data from student and staff surveys. Figure 36 shows the comparison of student (QS2) and staff (QT2) responses to questions concerning the better environment for learning theory. This demonstrates the difference in perspectives with students strongly favouring the real laboratory, while teachers are divided equally as to their merits. The Brandon style matrix provides a clear representation of the survey results which can aid analysis. Again, we need to be cautious in our interpretation of this data and compare it to the richer data provided by the survey comments and the interviews. This process was carried out in the sections above and demonstrates that this quantitative data is not well suited to a rounder understanding of experience.

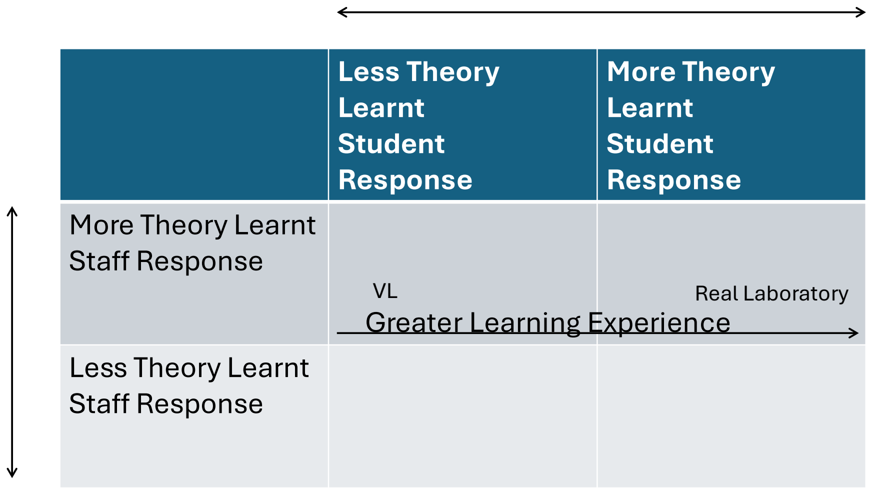

Figure 36 showing a matrix representation of the reported learning experience of students and the view of staff in real and VL, from survey data.

Summary

This section of the thesis addresses RQ3 through three different lenses. The first part concerns the development of concepts by considering the VL as a type of thought experiment. Following the work of Kuhn and Piaget (Kuhn, 1981), it is possible to show that thought experiments help to resolve 'a misfit between traditional conceptual apparatus and nature' (Kuhn, 1981, p. 27). If, as I believe, the VL can be regarded as an *embodiment of theory,* it becomes the stage for explicit thought experiments. So, it provides a way to challenge misconceptions, and misunderstandings of the consequence of theory (and so, by extension, students perception of nature).

The second strand of this section examines practical science and in particular VL in the light of Schulman's (2005) work on signature pedagogies. It seems clear that the practical science lesson in a real laboratory fits Schulman's (ibid) tripartite structure. There is a surface structure concerned with the rules and rites of the laboratory, in which students participate. Below this lies a deep structure based around the importance which both students and teachers attach to laboratory work as a vehicle for learning. This is all based on an implicit structure which sees practical science as an essential element of any scientists training: with a student asking, if you missed out on the practical element – *'Would you actually be a scientist?'*. However, for the VL it is less clear that it fits Schulman's (ibid) structure. It can be argued that the VL has a surface structure based on interactive quizzes and a points system. Additionally, there is a deep structure based on the transfer of theoretical knowledge, through planned activities in a laboratory like environment. However, it is less obvious that students engage with the implicit structure of the pedagogy – the VL is not, for them, an essential element of their learning.

The third area considered Is the positive contribution VL can make as a teaching tool. Both students and teachers recognise that the VL can enhance skills by allowing focus repetition of certain tasks.

Also, certain concepts, particularly abstract ones can be better illustrated by the VL than in the real laboratory. There is also the opportunity to build in scaffolding as an integral part of the VL activities. The VL can provide a less challenging environment for some students to develop skills and confidence in a safe environment. There are further benefits for independent learning by students not tied to traditional lesson times or the requirement to attend a physical laboratory. Teachers also believe the potential for individualised assessment in the VL is an important feature. It is often difficult in the real laboratory to judge who is performing which task and with what level of understanding. Additionally, the VL can provide a useful revision tool, which can be assessed on demand.

Summary of Chapter 5

Here I will attempt to give brief summary answers to the three research questions and some final remarks. As said previously the conclusions are arrived at by using an abductive approach or inference to the best explanation; with the caveat that for a small-scale limited study such as this it is not possible to be definitive.

RQ1: The extent to which students experience learning in a virtual laboratory as a mirror of reality?

To address this question, we have used the themes T1 – T6 set out in Chapter 4 and the ideas of Presence, Interactions, Motivation, Control and Consequences derived from these as a framework for the discussions. What appears to emerge from this study is that, generally, students believe in the results of the VL to the same extent as the real laboratory and so in that sense they see the VL as a 'mirror of reality'. This appears to be based on the acceptance that the theory and facts are the same in these two environments.

However, the students' experience in the two laboratories is different. The real laboratory gives a sense of presence, being in the moment, with genuine interactions with people and objects. There is a feeling of control which students have in the real laboratory and this with a sense of achievement motivates them. One of the important factors which distinguishes the two laboratories is the consequences of actions; students feel in the real laboratory it really does matter what they do. So, the VL does give real answers, but in the same way a textbook or lecture gives them. However, education is more than this: students feel, the real laboratory allows more of the experience of being a scientist.

RQ2: The extent to which students regard the results of experiments conducted in these environments as trustworthy?

In this question we are addressing a fundamental issue – 'what is truth?'. How do we know what to believe? It appears from the students' responses that there are two strands of trust which lead to the 'truth'. The first is in a sense the theoretical route. This is based on external authority – the universities, learned societies, large companies, textbooks, examination boards, the national curriculum; all these tell students, and teachers, the 'truth'. This is Orwell's (1961) 'mind of the Party', which defines for us the educational reality – the paradigm in which science is taught. This truth is accepted by students who see scientists as honest and trustworthy; who '*believe the teacher to be right'.* This is the paradigm which is exemplified by the VL. There is a second strand of authority – empirical evidence: students believe '*more because they saw it happen with their own eyes*'. This is evidence of the real laboratory. Normally, these two strands agree '*the lesson will have been sculpted in some way'* to show this agreement between the VL and the real laboratory. Teachers are *'confident that [VL] explains things correctly'* – the two paradigms coincide.

However, what happens if the two disagree? As one teacher put it *'a huge, like ridiculous conflict'* between the expected theoretical result of the VL and the '*the process in front of your eyes'* seen in the real laboratory. How do students respond to this dilemma? As might be expected there is a range of responses from '*70%, my results'* to *'I'd have to have a lot of evidence before I said the virtual programs wrong'.* However, what is unexpected is the apparent corelation between the confidence in the VL and the grade at A level. The two students who gained high grades were those with confidence in the VL, those who were unsure or favoured the real laboratory results received lower marks.

Overall, students seem to trust both the VL and real laboratory accepting both paradigms, based on theory and evidence. However, a greater trust in accepted theory seems to be more closely aligned with the examiner's expectations.

RQ3: The extent to which teachers can have confidence in the educational value of learning in the virtual laboratory?

There seems to be significant evidence that VLs help with academic achievement, both from this study and a range of literature reports, discussed in Chapter 2. These show that student grades are the same or better when using VL, compared to the real laboratory. In this study, a number of features of the VL have been identified as beneficial to learning. The VL can help develop a range of skills, although this range is less than the real laboratory, the VLs ability to allow for multiple repetitions and practice gives a significant benefit. The VL is also good at linking theory, particularly abstract theory, to practical activities. For neurodivergent and anxious students, the VL can provide a safer, less challenging environment to build up skills and confidence. Additionally, the flexibility of the VL is well suited to independent learning. The VL also provides a useful revision tool, which can be accessed on demand allowing students more autonomy over their learning. For teachers, the individualised nature of the VL is beneficial for assessment as this can be tailored and monitored for each student.

The VL also provides an opportunity for deeper thought and to challenge misconception as it provides an embodiment of a thought experiment. This can be used to explore aspects of learning which are not available in a normal laboratory experiment. A final area which has been investigated is that of real and VL as signature pedagogies. The evidence suggests that the real practical laboratory does provide what Schulman (2005) describes as a signature pedagogy, while the evidence for the VL is less clear.

Overall, summarising RQ1, RQ2 and RQ3, the VL provides a believable environment in which beneficial learning can occur. However, there are certain aspects of the experience missing compared to the real laboratory. While students and teachers trust the results from both real and VL experiments, there are potential conflicts in belief depending on the basis of the paradigm adopted.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

'The further we progress in knowledge, the more clearly we discern the vastness of our ignorance' (Popper, 1981, p. 84)

Introduction

In this chapter I am attempting to bring together the themes which appear to run through the data. By doing this I hope to give some sort of answers to the research questions as well as illustrating the themes which have emerged. The conclusions are drawn using an abductive approach or inference to the best explanation, as discussed in Chapter 3. Having said that, for a small-scale limited study such as this it is only possible to make tentative assertions, however the results do suggest some possible relationships and indicate areas for further study.

Chapter Summaries

Chapter 1 Introduction

Initially, the chapter sets out the problem and context of the research. VL is becoming a widely used tool at HE, but is it useful an in an FE environment? The general basis of science education in England is set out. Then the basic nature of the VL as an educational tool is reviewed. A more detailed examination of the difference between real and VL is made, leading to some of the underling features of a VL.

Chapter 2 Underpinning Ideas

Several studies have shown that VL can provide a valuable learning experience in HE and schools, particularly when used in conjunction with real laboratories. Students appear to be largely positive, however, there seems to be a preference for the real laboratory, related to emotional issues. There is a dearth of information about FE applications of VL.

Some of the literature concerning practical science as an educational tool, are reviewed and a number of specific outcomes can be identified. There are fundamental questions about nature of reality which are relevant to the use of VL. Sennett's (2009) 'mirror-tool' and Hanson's 'theory laden' perspective are considered in relation to the VL. The concepts of the scientific paradigm, tacit knowledge, signature pedagogies and the Gestalt switch are also introduced.

Chapter 3 Methodology

The VL is considered in relation to the three main areas of Greek philosophy: Ontology, Epistemology and Value Judgments. In particular, the development of knowledge through theory, is addressed as this is particularly relevant to VL. Different ways to determine the value or truth of a theory are discussed and compared.

The study takes an interactionist approach with the data largely gathered from interviews; this provides a framework for the description of the qualitative interactions which occur in the education environment. The aim of the research – to understand students experiences of real and virtual practical science; is set out and three specific questions are proposed. The reasons for choosing thematic analysis of the data are discussed. Also, some of the details of the data collection methods are given.

Chapter 4 Data Analysis and emerging themes

This chapter records the data collected through online surveys and face-to-face interviews with students and teachers. The survey data indicates that students seem to appreciate the extra perspective the VL provides, the clear methodical presentation and opportunities for questions to check understanding. However, they largely prefer working in the physical laboratory, which is more engaging, offering the opportunities for developing hands-on skills, teamwork, communication and 'because its different from doing it by yourself in real life than virtually'.

In interviews students and teachers expand on the value of the VL for learning theory and method; but also, the lack of interactions with both people and objects with in the VL. The real laboratory then provides a richer experience which is heightened by the feeling that actions in the real laboratory have real consequences.

Chapter 5 Discussion of Themes and Findings

This study suggests is that students believe in both the results of the VL and the real laboratory. They accept facts and theory in both environments. However, their experience of presence, interactions, motivation, control and consequences, are less in the VL.

The trust students put in the VL comes from external authority – the universities, learned societies, large companies, textbooks, examination boards, the national curriculum and they '*believe the teacher to be right'.* There is a second strand of authority, born of experience – empirical evidence. If these two paradigms coincide all is well – if not the students' need to make a choice – which appears to be enlightening.

Students and teachers find that certain features of the VL are beneficial to learning. Such things as developing certain skills and a theoretical understanding can be achieved in the VL. It is also beneficial for anxious and neurodivergent students, while providing a useful platform for independent learning, revision and assessment.

Why is this study useful?

This work investigates an area of education which appears not to have been well studied. There is therefore considerable potential for contributions to knowledge. The following list illustrates some of the areas in which this study is novel:

1. There are very few studies where students have been interviewed to obtain their views on VL, in any context (Sellberg, Nazari and Solberg, 2024).
2. There are a limited number of studies which consider the pre-university use of VL.
3. There appear to be no peer reviewed studies of VL implementation within the FE sector.
4. There do not appear to be any studies in which teachers have been interviewed about student experiences in VLs and very few about practical science in general.
5. There are very few studies involving practitioner research into VL.
6. There do not appear to be any studies investigating students trust in VLs, or the perception of risk or jeopardy on motivation; and very little concerning real laboratories either.
7. There appears to be little or no work investigating signature pedagogies in relation to practical science: and no studies concerning VL.
8. There appear to be limited studies which view virtual laboratories from theoretical perspectives, such the work of Kuhn (1981, 1996), Hanson (1962), Bloom (UArk, 2013) or Sennett (2009). Nor are there studies concerning the possibility of dual paradigms operating, or the role of pattern recognition, or the application of Gestalt principles within practical science or science education in general.
9. There do not appear to be any studies which address the issues concerning the choice of VL, beyond purely practical considerations.
10. There do not appear to be any studies which have investigated the relationship between practical science (real or virtual) with A level performance.

What has been found?

The contribution of this work to several areas is now briefly reviewed.

Further Education

The study provides a report of a series of surveys and interviews concerning the implementation of VL within an FE college. This work focuses on a very limited application of VL with A level students. However, the data provides a wider illumination of the experiences of students and teachers within an FE setting. This gives voice to the thinking of pre-university students whose focus, motivation and abilities are likely to be different to undergraduate or post graduate students. The interviews indicate students are less confident in their own abilities than university students might be, while showing mature thinking when considering, for example, their trust in the VL.

The use of interviews allowed students to engage with and expand on a number of issues which could not be adequately addressed in survey answers. The data from seven student interviews provided a rich illumination of students views and experiences in real and VL. There seems to be a lack of academic interest in the experiences of teachers in practical science education and VL in particular. This study provides data from teachers showing their views on both practical science and VL. The interviews with two science teachers give some wide-ranging insights into practical science teaching in FE.

Practitioner Research

A practitioner research study provides a unique 'insider' view of the topics studied. Thus, due to my established relationships with staff and students I was able to discuss issues at depth that would not have been accessible to an external researcher. The benefit of shared experience allowed the interviewees to use mutually understood shorthand and references which would need to be explained at length to another researcher. This allowed flow and depth to the conversations to be developed in the interviews. There is also an element of trust, which was particularly evident in the discussions between students and some of the aside remarks of the teachers. This is especially relevant to the investigation why students, and teachers, believe in the results of the VL or for that matter the real experiment. This has enabled their reasons for trust to be examined and discussed in some detail.

Theoretical framework

The works of three important thinkers have been used to frame the discussions concerning VL. Although the work of Hanson (1962) and Kuhn (1996) predate the widespread use of VL, their work is very relevant. Hanson provides the concept of 'theory-laden' observation and significant discussion of the interaction of theory and experience, which is germane to the study of VL. Kuhn develops the 'paradigm' as the defining unit of scientific experience, and this underpins some of the discussion of the verisimilitude of VL. It informs the discussion of the potential Gestalt switch between paradigms which is considered in this work. The concept of a dual paradigm proposed, where students experience is described separately by:- a real laboratory paradigm, based on empirical evidence and a VL paradigm, based on theory and trust. Additionally, evidence is presented of a Gestalt like switch between the two. It could also be useful to consider the VL as an embodiment of a *thought experiment* and this perspective has been explored in light of the work of Kuhn (1981). Another perspective, due to Schulman (2005), is that of a 'signature pedagogy'. It is possible to show that practical science education seems to fit with Schulman's criteria for a signature pedagogy, however this is a less certain for the VL.

The work of Sennett (2009) is important in relation to the interactions present both in the real and VL. These relate to both people and objects; the different interactions can be viewed from range of different perspectives. Sennett's (2009) concepts of a 'mirror-tool' and 'prehension' are also applied to the study of the VL and show that VL examined acts more as a 'robot' – enhancing certain features of practice; than a 'replicant' – a faithful reproduction.

Bloom's taxonomy (UArk, 2013) has been applied to the analysis of both real and VL experiments. The results for VL show a close alignment with Bloom's structure, however learning in the real laboratory shows a very different structure. This could lead to difficulty in facing higher level cognitive demands before building a lower-level framework. This analysis agrees with some of the points made by Rau (2020) concerning cognitive load. The concept of patterns as a basic unit of knowledge is considered in relation to science and in particular VL. This provides a way of relating knowledge development through the identification implicit and explicit patterns, in particular, those underpinning the VL. Another perspective which has been useful is that based on Gestalt principles. These are related to the recognition that the VL exists as more than the sum of its parts. Their use is demonstrated by analysis of the specific case of the RSC VL.

Educational implementation

This study has produced some interesting results concerning the trust students place in the results produced in real and VLs. This is related to the trust students have in the teacher, technicians and those who produced the VL. Students seem to implicitly trust both the real and VL to give true results. When asked to consider a conflict between these they gave a range of answers; unexpectedly, there appears to be a positive relationship between confidence in the results of the VL and performance in the A level exam. Interestingly, students seem to value the risk present in the real laboratory and are motivated by the real consequences of their actions compared to the minimal risks in the VL. Students report feeling more in control in the real laboratory when their choices and actions really matter. Also, they feel more motivated and engaged knowing others are relying on them.

The research questions are now briefly reviewed; as with all such qualitative questions there is rarely a correct answer or even a single answer. So, some tentative descriptive answers and conclusions are proposed.

RQ1: The extent to which students experience learning in a virtual laboratory as a mirror of reality?

There seems to be a fairly general acceptance from teachers and students that the results of a VL are close to those seen, or expected, in the real laboratory. Interviewees seem to regard any differences in results as due to poor experimentation rather than failings in the VL. So, in this fundamental sense the VL mirrors reality. However, students do not have the same experience in the VL, as in the real laboratory. They identify a number of differences which can be loosely grouped under five headings: Presence, Interaction, Motivation, Control and Consequences. – these factors give a richer experience within the real laboratory.

The considerations of the different arrangement of cognitive tasks between the real and VL, both from student comments and the analysis based on Bloom's taxonomy (discussed in Chapter 2), suggest that learning may occur differently in the two laboratories. These might be considered to be operating in different, and possibly incommensurate, paradigms. Therefore, learning may be a different experience in the two laboratories. Firstly, students are learning different things, the VL is very much theory based with some development of method and skills; while the real laboratory also provides these, there is additional learning in areas such as: presence, interaction, motivation, control and consequences. Secondly, although the theory and content learnt is similar, it is probably learnt in a different way (see Rau, 2020).

RQ2: The extent to which students regard the results of experiments conducted in these environments as trustworthy?

As suggested for RQ1, above, students and teachers tend to trust the results of both real and VL. The underlying question for RQ2, is then *why*? There appear to be two distinct reasons for belief: one, which could be described as external, the other as internal. These operate for both laboratories, but there is more reliance on the external with the VL and internal with the real laboratory.

Trust from the 'external' route is derived from external authority such as: governments, universities, institutions, corporations, textbooks, syllabuses, peer review, experts. These help to define an 'objective truth', which Kuhn (1996) would describe as the prevailing paradigm. Students essentially, trust the honesty and integrity of scientists so regard them and their work as trustworthy. This trust is then transferred through the education system and in particular, through their teachers. The students' trust in teachers seems to be a very important factor in determine how trustworthy they regard the real and VLs. There appears to be a code, developed in schools, where students accept, that teachers have '*a status above us, so we kinda believe'.* While this seems to be the case at FE the situation may be different for older students at university. Interestingly, the older student (D, 28) was the one who express the most scepticism about both types of laboratory – *'people make mistakes, it doesn't matter if it's in real or in virtual ones'.* So, in general, students seem to believe in both laboratories because they are part of the accepted educational paradigm – normal science.

The second, 'internal', strand of belief is that of empirical evidence – '*because they saw it happen with their own eyes'*. In this case the students are putting trust in their own experiences *'you can like touch it'* **…** *'It's actually there'.* However, Hanson (1962) tells us that all observations are 'theory-laden', so what we experience is in part determined by what we already know, and this is determined by what we have been taught within the accepted educational paradigm – normal science.

Although the strands appear independent and in some senses are; ultimately, they are interrelated, as both are underpinned and moulded by the education system. If, as appears to be the case for the students, we regard the strands as separate, we can consider what happens when there is a conflict between the two. The students and teachers seem to regard the authority of the VL to be largely drawn from the external strand; while the real laboratory is supported by the empirical strand. By posing the thought experiment – what if the two significantly disagree, we are able to investigate which the students trust more. This is illuminating: two students appeared to trust the VL more, four on balance favoured the real laboratory, with one '*in between'.* What is interesting, and maybe significant, is that the two students who favoured the VL, and so trusted the external authority strand more, achieved high grades at A level: while the other students received low grades or were ungraded. This suggests there is, perhaps unsurprisingly, a correlation between acceptance of the authority of the prevailing paradigm and exam success, as Holman (2017, p. 20) points out 'performance in science tests does not correlate with practical science … Practical science may not be the most efficient way to prepare for written tests'.

Summarising, there appear to be two paradigms operating: one is theoretical, deterministic, authoritarian, outcome aligned, textbook and syllabus based, exemplified by the VL; the other, experiential, practical, tangential, complex, observation and interaction based, exemplified by the real laboratory. The first is aligned with exam success, but without the second *'Would you actually be a scientist?'*

RQ3: The extent to which teachers can have confidence in the educational value of learning in the virtual laboratory?

The responses from students and teachers recorded in this work show that VLs have a place in teaching and learning. Students value the ease and convenience of using the VL for providing pre-laboratory training, step-by-step method, post laboratory revision and illustration of theory. Teachers also value these points, while additionally recognising that the VL can provide a safe space for anxious or neurodivergent students and providing a route for individualised learning and assessment.

Although this study does not attempt to assess students' performance against learning outcomes, there significant evidence from studies in HE to show that VLs contribute to academic achievement. The comments from teachers and students would suggest that this will also be the case in FE. The comments presented in this work suggest that '*the theoretical part is'* shown in the VL and this illustrates *'the theory behind an experiment'* and *'solidifies the theory'.* The VL can also help students practice skills allowing multiple repetitions and instant feedback. This is particularly true for the measurement and maths skills which are part of quantitative experiments.

However, there are areas where the VL does not provide the same learning experience as the real laboratory. These might be described as 'soft skills', qualitative values associated with tacit knowledge developed by *doing.* Students identify a number of areas where they feel the experience in the VL is less than that in the real laboratory. These have been identified in the responses to RQ1, but it is worth emphasising the effects on teaching and learning. Students develop intellectually and emotionally through their interactions with others; this social aspect of learning is not generally available with the VL. Students also develop manipulative and spatial skills in the real laboratory which may also increase their tacit understanding of the concepts involved; this may not be the case when '*clicking mindlessly in a virtual lab'*. Similarly, the students have a feeling of control in the real laboratory where *'the decisions you make, actually make an impact on actual chemicals'.* There is a feeling of control and that *'consequences mean more in a real lab, so it makes you more engaged with it'.* This promotes motivation as *it 'engages you more, because you have to think about the … consequences of your actions'.* The VL can therefore provide a valuable teaching tool, 'but can never be a full replacement' for the real laboratory.

Two specific areas of learning were investigated in some depth. The first was the concept of the VL as the embodiment of a thought experiment. Using this model, we can see how the VL can provide a richer learning experience. Students are able to access 'real' scenarios and experiments not available in normal laboratory experiments. Learners can test concepts and explore misconceptions in a safe but challenging environment. By investigating 'a misfit between traditional conceptual apparatus and nature', the student is 'helped … to modify their conceptual apparatus' (Kuhn, 1981, p. 15) and 'learn about their concepts and the world together' (ibid., p. 17).

A second area investigated is that of signature pedagogies. Schulman (2005) suggest that certain modes of teaching can be regarded as signature pedagogies, for particular areas of learning. The 'science practical' seems to fit well with Schulman's (2005) criteria. Students' experience working in the real laboratory is seen by many of them as something which is an integral part of science education. There is an almost ritualistic quality to the practical lesson, which can be analysed within Schulman's tripartite structure. However, for VL, it is less clear that it fits Schulman's structure and so does not appear to have all the features of a signature pedagogy.

What is education for?

The results of this work point towards the fundamental question of the purpose of education, in particular, science education. The real laboratory and the VL offer us two models, two paradigms perhaps., based on different premises:

The first is curriculum focussed, theoretical, deterministic, planned, scaffolded, outcome aligned, top-down, following a predetermined path towards a 'truth'. For Kuhn (1996) this is the route of 'normal science', accepting the prevailing paradigm and working within it to solve any remaining puzzles. This is embodied by the VL, externally designed following a set of rules which fit the paradigms of the creator.

The second is observation focused experimental, practical, experiential, organic, process aligned, bottom-up, following changing directions towards 'truths'. This is closer to Dewey's (Biesta and Burbules, 2003) concept of enquiry, an interaction between the student and their environment, in which both are modified. This is the case in the real laboratory, where any planning and predetermination is modified in the complex interactions.

These descriptions are intended to emphasis the differences between the two cases, in a real lesson, theory and practice – normal science and enquiry are often mixed. However, it is important to see that there is a fundamental tension in the teaching of science – which may be why many students find it difficult. For maths there is one right answer; for history the use of multiple perspectives is considered essential; but for science – is there one right answer: aligned with the mark scheme; or is the observation in the laboratory closer to the truth? I am not sure that the student, or indeed the teacher, knows. So, should teachers concentrate on a specification aligned curriculum, teaching students to pass exams and succeed within 'normal science' or to allow students' enquiry to develop their own understanding?

Recommendations for practice

In this section there are some observations and suggestions about how a VL could be implemented in an FE environment. Due to the exploratory nature of the study, the recommendations are fairly general and intended as areas for consideration rather than prescriptions for success. The first suggestions are largely practical, while the later ones focus on areas for reflection.

- Both this study and the literature surveyed suggest that both VL and real laboratories can provide useful educational experiences. They are best used as complementary methods, each adding a different perspective for the students.
- This work suggests that the VL should not be viewed as replicant or replacement for the real laboratory, but something different. The VL appears best suited to providing a different perspective on theory and a scaffolded structure for learning practical methods and techniques. This maybe particularly useful before and after a corresponding real practical.
- The VL provides a useful addition for anxious or neurodivergent students who need practice, extra processing time, or even as a substitute activity. The VL can allow students to work in a

safe, predictable, low risk environment, where they can develop confidence and skills. So, it may be useful to set a relevant VL prior to a practical lesson.

- The convenience of the VL can be valuable for students who wish to work outside the normal lesson times, particularly for independent learning.
- The choice of VL is an important factor: it is important for the confidence of both students and teachers that the VL comes from a respected and well-known organisation – this builds trust in the results. Careful consideration of the alignment of material in the VL with the intended learning objectives should be made. For example, the VL may provide theory and method, but not development of manipulative or observational skills.
- There is a range of complexity for available VLs. For some objectives a very simple VL with minimal interaction may suffice e.g. illustrating theory; for others, say learning a new experimental method – significant features and interactions will be required. There may be a cost or computational limitation which also affects this choice.
- The real laboratory provides several valuable features which are less present in the VL e.g., presence, interactions, motivation, control and consequences. It is important to consider the balance of VL and real activities to allow these elements to be developed.
- The VL can be a useful tool for individualised assessment; providing teachers with insights which are difficult to obtain in a real laboratory. For this aspect to be useful, careful consideration of the alignment of activities with objectives is important.
- This work suggest that a dual paradigm may operate in science education, with practical and theoretical aspects being processed differently by students. The VL would appear to align more with the theoretical area, so it is important to try to use it as a bridge to the practical – real laboratory. By a careful choice of theoretical and practical activities the VL could give students the opportunity to a greater insight between what is happening in the laboratory and the underlying theory.
- As the VL is based on theory, it is important for teachers to explicitly understand the nature of what underlies the programs. This is particularly true and increasingly difficult as the VLs grow more and more complex.
- Experience is an important feature of learning and students value that in the real laboratory more than in the VL. The advent of virtual reality technology may change some of these considerations, but for the simpler VLs it is important to ensure students still have the opportunity for real interactions.
- The importance of patterns as a unit of knowledge has been discussed in this work. This is an area where teachers might reflect on the way material is presented. The demonstration of a pattern of reactions or a grouping of results might be more powerful, than a single example – however well it demonstrates a point.
- Teachers need to consider their underlying educational philosophy, are they focussed on aligned achievement of quantifiable exam success or on the development of more tacit skills and knowledge. How can they bridge the two?

Limitations of the study

This has been a limited exploratory study, so the results are restricted and conclusions tentative. There follows a discussion of some specific issues which might limit the validity or application of this study.

Investigator

It is the prevailing paradigm which determines the rules we work with. I am working within an educational paradigm which determines how I, and others, view this research. As part of a PhD programme the study needs to fit into the Universities requirements and expectations for an appropriate study and thesis. Moreover, I am also working within the paradigm of science education within a FE college, teaching A level chemistry: these will affect my perspective. Similarly, I am a trained scientist, a member of the RSC and science teacher, so I have an investment in the current scientific paradigms; which will also affect my choices and judgements. I have limited experience as a qualitative researcher: I am still developing my skills in this area.

Methodology

This is an explorative study so the aims are broad, and it may be difficult to rely on specific points. The methodology adopted is appropriate to an explorative study, however further work is required to reliably generalise these results. The data recorded in Chapter 4 and the Appendices, provides a resource to assess the applicability to other settings.

This is practitioner research study, which while having a number of advantages, does mean care must be taken to reduce bias. Inevitably, as I have shared experiences with my students, so we may also have shared biases. There is also an imbalance of power, so students may modify their responses towards what they think I might want. Additionally, the teaching staff are also work colleagues and so this may influence the nature of their responses.

Study structure

The study is based on a very small sample. The surveys were given to all the students studying A level chemistry and to the majority of the staff teaching science at level 3 within the college. The interviewees were drawn from students and staff, who had responded positively to a request for an interview either in the survey or in class. The sample turned out to be broadly representative of the in the range of A level grades, male/female ratio and age profile of the students; although this is less important in an explorative study, such as this.

The study was carried out over a relatively short time period and the responses may have been influenced by the proximity to the COVID-19, pandemic and resultant lockdowns. The interviews focused on the experience of one specific VL, from the RSC. Although this might be regarded as typical of a number such VL applications it is not representative across the vast range from simple animations to complex VR multifunction VLs.

Table 42 showing opportunities for additional research into real and VL

Field	Immediate projects	Longer term studies
Educational philosophy	The study of 'academic trust' as feature of learning, using the real and VL as proxies for investigative and authoritarian paradigms. The investigation of risk or jeopardy as factors in motivating student learning and any effect on student performance.	The investigation of using patterns as a unit of knowledge and internal pattern change as learning. A deeper study of external and internal authority and teachers' authority in defining 'truth'. This is also relevant to the concept of the "digital twin" and issues such as the computer modelling of climate change (En-ROADS, 2024). An exploration of how tacit knowledge maybe generated differently in real and VL. The establishment of whether the real and VL, provide good proxies for 'practice' and 'theory'. A deeper investigation of VL in relationship to the concepts of praxis, poiesis, theoria and phronesis.
Science education	A wider study to confirm the finding of a relationship between academic performance and confidence in the VL. Including the development of a robust methodology for this study.	Exploration of the operation of a dual paradigm in science education – the separation of theory and practice. Investigation of VL as a practical or theoretical or bridging pedagogy for science education. A deeper exploration of signature pedagogies to illuminate any differences between real and VLs.
Further education	A deeper investigation of FE students' concept of 'academic authority'. Is this different to other settings?	A wider exploration of the different experiences and attitudes of FE students to teacher authority and the relationship to educational attainment, compared to other settings. Whether 'trust' in real and VL results is different between FE pathways e.g. A level, Access, T level.
Virtual laboratories	Comparison of students' experiences of the real laboratory, a structured VL and an unstructured 'enquiry' based VL.	Investigation of a wider range of VLs as methods for science education focusing on features such as presence, interaction, motivation, control, consequences, identified in this study. The use of different types of applications, for example VR, and how might this affect students' experiences. Development of a series of studies to investigate VL from the perspectives of Kuhn, Hanson, Sennett, Dewey, Popper, Feyerabend and others.

Opportunities for additional research

This is an explorative study which provides a starting point for different lines of enquiry. The section above indicates a number of areas in which this work appears to be novel. Standing in the middle of any empty field we could head off in a number of directions. Table 42 shows a number of potential studies which this work has suggested.

Summary of Research Findings

These are tentative findings based on limited survey results and a small number of interviews with the students and teachers who contributed to this study.

1. Students believe in the results of real and VL experiments.
2. Students feel more present and engaged in the real laboratory.
3. Students tend to feel more motivated in the real laboratory.
4. Students value the interactions with people and objects that the real laboratory affords.
5. Students feel they gain more skills in the real laboratory.
6. Students feel more in control in the real laboratory.
7. Students value the risks and consequences in the real laboratory.
8. Students' belief in both laboratories is partly based on the authority of their teachers.
9. Additionally, students believe what they see before their own eyes in the real laboratory.
10. Trust in the VL is based on the authority of universities, institutions, scientists and teachers.
11. When this trust is tested, students make different of choices about which laboratory to believe. Students who trust the VL results more than the real laboratory tend to do better in their A level exams.
12. Teachers believe in the value of practical science for teaching a range of skills.
13. Teachers value VL as an additional resource for teaching.
14. Students and teachers value the flexibility of the VL.
15. The VL can be considered as an embodiment of a thought experiment and can change learners concepts.
16. Practical science appears to have the characteristics of a signature pedagogy, while the VL does not seem to have all the necessary characteristics.

Concluding remarks

In practical science, both in the real and VL, the student is a complex environment without a full comprehension of the whole. This requires students to make judgements in an uncertain environment and take action based on these. Education in the VL is more suited developing theoretical knowledge, theoria. While the wider practical skills developed in the real laboratory may help to develop phronesis, a quality which may be of even greater value in our complex world. Part of the judgment required in science concerns the discernment of the truth. This study suggests that some students may see this in different ways at different times. They accept the VL as true, because they are told it is by those they trust, teachers, scientists, textbooks, universities, large companies, even the government. The VL perpetuates the ideas of the accepted paradigm of 'normal science'. This is also felt by teachers who follow the directions of the DfE, OFSTED, and their employers; they are part of the system, authority is channelled through them. The VL then reflects the accepted theories of science, but as it is itself complex few will fully understand the software interactions and know why the results should be true. The real laboratory offers a different view – a reality based on interactions, touching, hearing, smelling, but above all seeing. Seeing the world as – as it really is? Or in the way we have been taught to see it with all our preconceptions and theories. So, we are perhaps left with the question – should students be taught to pass exams, achieve success within the paradigm of normal science, perhaps to conform the expectations of society, or should they be encouraged to enquire into the truth? But then – 'What is truth?'

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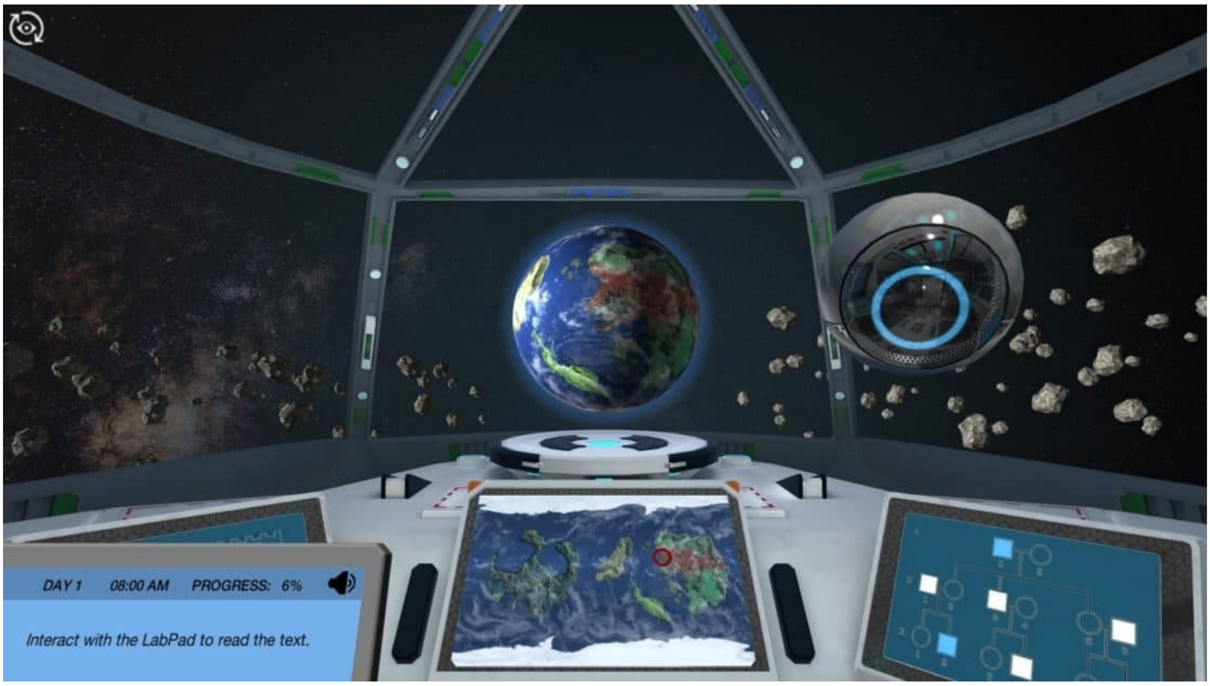
APPENDIX 1

Some currently available VLs

(Including hyperlinks)

Labster



[Intro video]

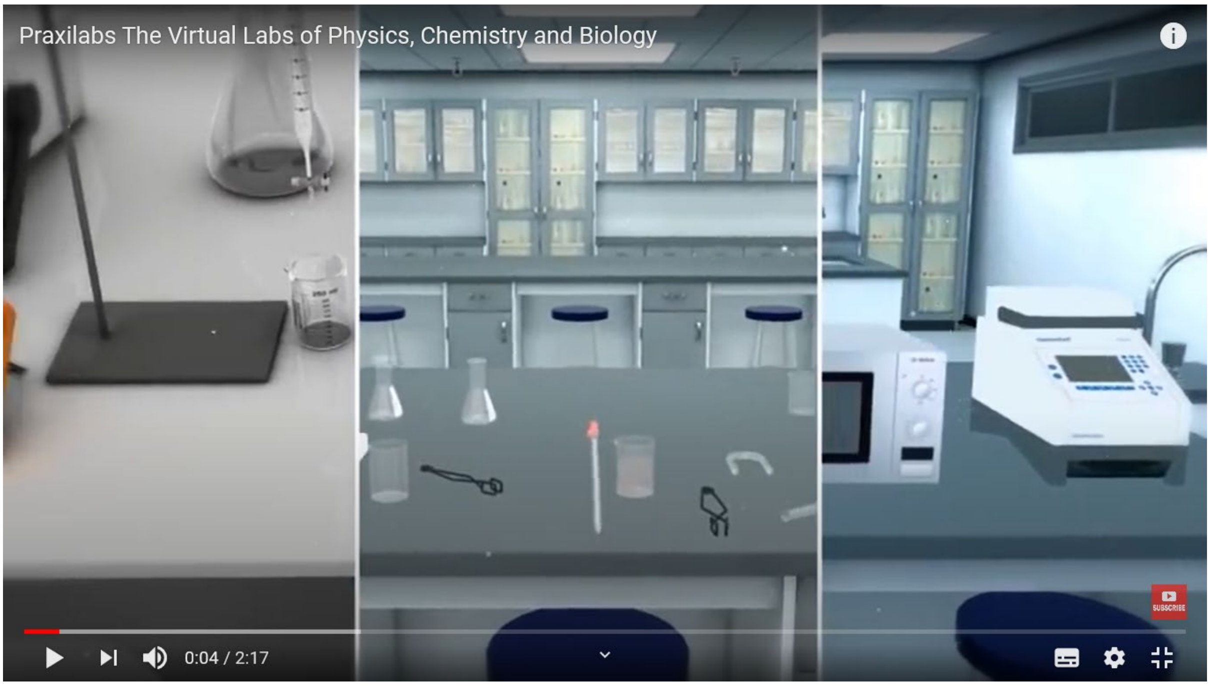
[Simulation catalogue]

[Testimonials]

This is a highly sophisticated suite of programs across biology chemistry physics engineering and medicine. These tend to be fixed labs with a scenario that students follow, gaining points for activities.

Research papers on Labster at https://www.labster.com/research/

Praxilabs

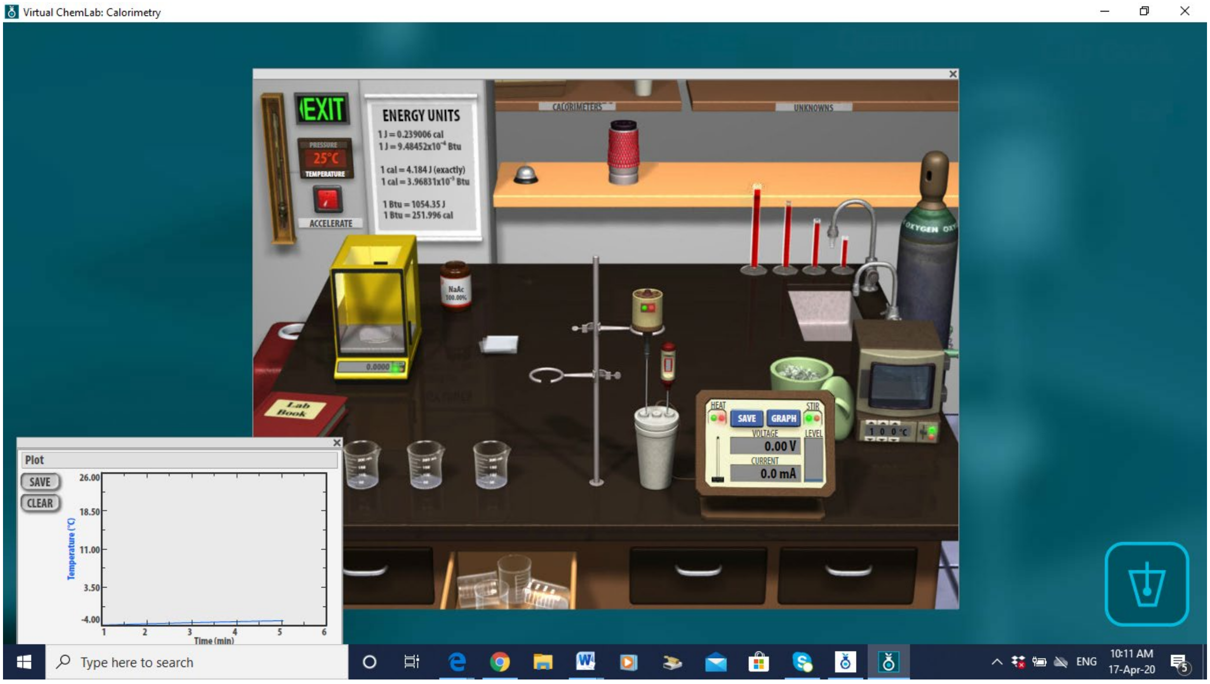


The link gives the [full list of experiments](#).

More information at https://praxilabs.com/en/virtual-labs

Beyond Labz

https://www.beyondlabz.com



This VL seems to behave like a lab where you are able to construct your own experiments from the available equipment. There are a number of worksheets available to run standard experiments. The system appears versatile, so with time bespoke experiments could be set up effectively.

General labs

PhET Interactive Simulations

PhET, based at the University of Colorado at Boulder, offers large range of free physics (106), chemistry (53) and biology (19) simulations. Users can search by subject and grade level and can be browsed at https://phet.colorado.edu/en/simulations/browse. Many have been translated into different languages.

The Open Science Laboratory -- "An initiative of The Open University and The Wolfson Foundation"

Virtual Laboratories in Probability and Statistics at the University of Alabama in Huntsville's Mathematical Sciences Department.

MERLOT https://www.merlot.org/merlot/index.htm provides an enormous amount of online materials for science including virtual labs.

Chemistry Labs

Below is a list of freely available online chemistry lab resources, including general chemistry and organic chemistry simulations.

RSC provide two free scenario led virtual labs one for titration the other for aspirin synthesis and analysis at http://www.rsc.org/learn-chemistry/resources/screen-experiment

- Chemistry Solutions: Featured Simulations

  Each issue of *Chemistry Solutions*, the periodical of the American Association of Chemistry Teachers, contains a simulation. This page collects and describes simulations from past issues.

- MERLOT Simulation Collection

  The Multimedia Educational Resource for Learning and Online Teaching (MERLOT) at the California State University has collected descriptions and links to a huge number of simulations, with peer review ratings and comments, and information on their appropriateness for various levels.

- ChemCollective

  The ChemCollective, organized by a group from Carnegie Mellon, shares virtual labs, simulations, and molecular level visualizations for chemistry.

- Mixed Reception

  This ChemCollective activity might be described as a murder mystery for chemistry students. Students can "interview" suspects by viewing videos, investigate the crime scene using images, and analyse evidence from the crime lab.

- CK-12 Chemistry Simulations

  Nearly two dozen simulations cover topics like average atomic mass, solubility with rock candy, and freezing point depression with salting icy roads.

- Titration Screen Experiment

  Get students ready for a hands-on titration by allowing them to run one virtually first.

- goREACT Virtual Chemistry Lab

  This drag-and-drop lab environment from Chicago's Museum of Science and Industry lets you experiment with different reactions.

- ChemReaX

  Users can model and simulate chemical reactions, focusing on thermodynamics, equilibrium, kinetics, and acid–base titrations. It is designed for Advanced Placement high school and undergraduate students and teachers.

- Molecular Workbench

  The Molecular Workbench offers simulations in multiple sciences, along with tools for both teachers and students to create their own simulations. Teachers can also create their own curriculum modules with embedded simulations.

- Virtual Chemistry Experiments

  Professor David N. Blauch of Davidson College presents several interactive experiment simulations on topics such as equilibrium, kinetics, crystal structure, phase changes, gases, and more.

- General Chemistry Interactive Simulations

  This page, maintained by chemistry professor William Vining, has simulations that cover a wide range of chemistry concepts, keyed to chapters in a general chemistry text.

- Electrolyte Solution Simulation

  A version of an electrolyte solution simulation from John Wiley and Sons is available at the General Chemistry Online! page. It allows the user to select different cations and anions. Data can be logged and downloaded as an Excel spreadsheet.

- Simulations for Chemistry

  Professor Gary L. Bertrand’s (University of Missouri–Rolla) page offers many simulated experiments, such as “The Case of the Five Droppers,” a virtual presentation of five reagents being mixed in different ways to produce various precipitates and gas bubbles, and a coffee cup calorimeter activity.

- Virtual Laboratory: Ideal Gas Law

  A virtual lab from the University of Oregon allows one to perform three experiments. The user controls the action of a piston in a pressure chamber filled with an ideal gas, illustrating.

Virtual Chemistry Laboratory at the University of Oxford Department of Chemistry.

ChemCollective Virtual Labs -- "an online simulation of a chemistry lab ... designed to help students link chemical computations with authentic laboratory chemistry. The lab allows students to select from hundreds of standard reagents (aqueous) and manipulate them in a manner.

Virtual Lab Simulator – From the ChemCollective. It started as the IrYdium Project’s Virtual Lab. There is extensive documentation for the lab, including an instruction video. The Java lab applet is translated into Spanish, Portuguese and Catalan

Virtlab: A Virtual Laboratory – Registration required, but you can join Virtlab for free.

Virtual Chemistry Experiments – Chemistry and Physics applets and phylsets from Davidson University. Some exercises are currently broken and others (like the **Chemical Equilibria** exercises) work fine.

Dartmouth ChemLab – This site has some very good interactive virtual labs plus a terrific interactive periodic table.

Virtual Chemistry Lab – From the University of Oxford. Virtual experiments as well as webcasts on chemistry topics

Chemistry Experiment Simulations – From Iowa State University. Includes simulations/virtual lab, balancing equations and a **pH meter**

Hi! Hydrogen – Interactive online chemistry lab

Chemistry Homework: Interactive Tutorials – From the CSUDH Chemistry Department. Includes interactive tutorials on significant figures, quantum numbers, gas laws, thermodynamics, nomenclature and more.

ACD/ChemSketch Freeware – Free chemistry software to download.

Web-Based High School Chemistry Simulations – From Education Development Centre, Inc.

Virtual Chemistry Book – Not really an online lab but has PDF and web files on all major concepts in chemistry with excellent graphics. It also has tutorials on selected topics such as redox reactions, acid-base titrations, and aquatic chemistry.

The Interactive Library – This EdInformatics.com site is a list of links to interactive **Chemistry** and **Biochemistry** sites. Some Java applets are standalone, and some come with lesson plans and notes.

General Chemistry Jeopardy Games – From the University of Pittsburgh

Y Science Laboratories – Realistic and sophisticated simulations covering chemistry, physics and planetary motion, from Brigham Young University

ChemCollective http://chemcollective.org/vlabs

Available simulations are listed here:

- Stoichiometry
- Thermochemistry
- Equilibrium
- Acid-Base Chemistry
- Solubility
- Oxidation/Reduction and Electrochemistry
- Analytical Chemistry/Lab Techniques Stoichiometry

Commercial products

- **Online Chem Labs** – Full set of virtual interactive chemistry laboratory experiments

- **Late Nite Labs** – Includes both Chemistry and Biology labs.
- **ChemLab** – Interactive fee-based service. You can design your own simulations. Go to the downloads page for a free evaluation trial.
- **TeqSmart Learning Objects: Science** – Includes a Titration exercise.
- **Chemistry LabPaqs** – Hands-on laboratory experiences

Physics Labs

Online physics lab resources, including condensed matter, atomic/molecular and particle physics.

PhET Interactive Simulations
PhET, based at the University of Colorado at Boulder, offers over 70 physics-based simulations. Users can search by subject and grade level https://phet.colorado.edu/en/simulations/browse. Many have been translated into different languages.

FlashyScience https://flashyscience.com

Physics and engineering labs from Sheffield University. A small number of fairly sophisticated labs with work sheets etc. Account now set up until August 2021.

Algodoo: A free physics-based virtual laboratory for Mac or iPad.

- **NTNU JAVA Virtual Physics Laboratory** – Includes English and Chinese languages.
- **MyPhysicsLab** – Physics Simulation with Java
- **Virtual Physics Labs** – At Central Connecticut State University (CCSU). It's a link directory to other educational physics sites.
- **The Interactive Library** – This EdInformatics.com site is a list of links to interactive physics sites. Some Java applets are standalone, and some come with lesson plans and notes.
- **Physics Classroom**
- **FearOfPhysics.com**
- **Physics Applets** – From the University of Oregon
- **UCLA's ePhysics**
- **UCLA Physics and Astronomy Lecture Demonstrations**
- **Online Physics Textbook**
- https://www.ises.info/index.php/en - University of Prague 18 physics experiments, plus remote access experiments.

The following physics laboratory simulations and educational learning exercises are available for a fee.

Commercial products

VPLab provides:

01. Astronomy

02. Charged Particles

5. 2.3.B Linac
15. 2.4.C The Linac

03. Circular Motion

04. Communications

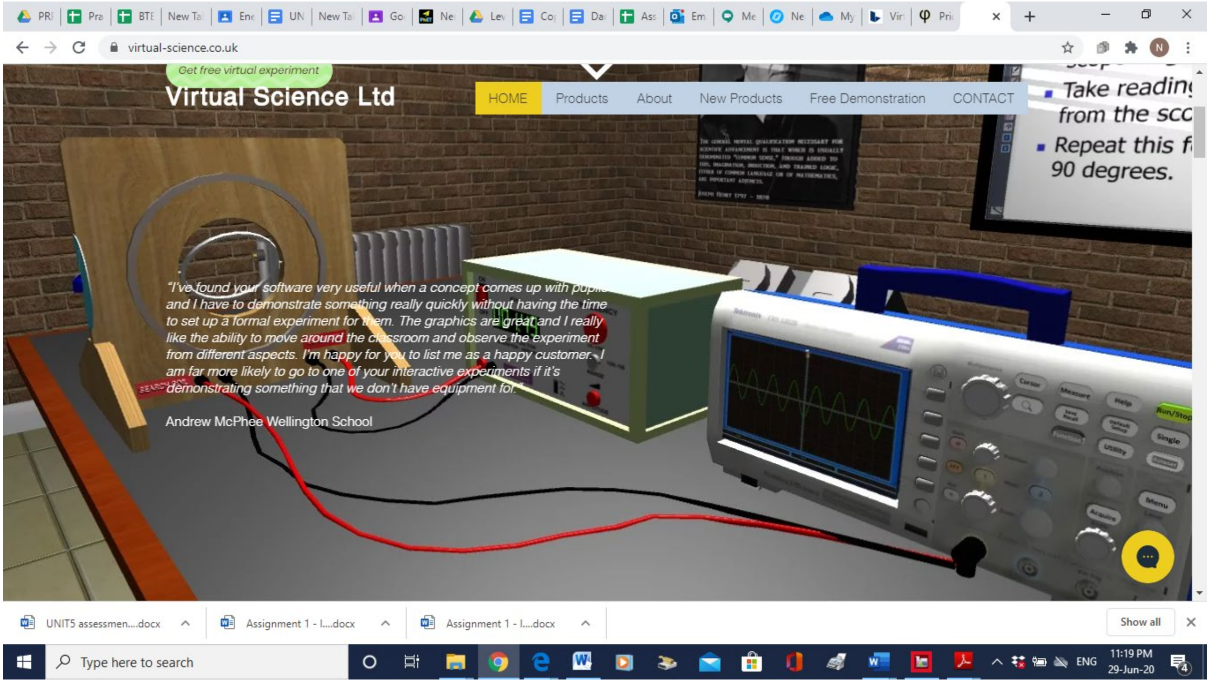
2. 4.2. Digitising

05. Dynamics

06. Electricity AC

Virtual Science

Mainly physics experiments covers the requirements for A level and Access Physics. Experiments specifically designed to match A level requirements.



[Virtual Science Ltd - Online Physics experiments (virtual-science.co.uk)](virtual-science.co.uk)

Astronomy Labs

Below is a list of freely available online astronomy and space science labs and resources.

- **Google Earth** – Lets you fly anywhere on Earth to view satellite imagery, maps, terrain, 3D buildings and more. Explore galaxies in outer space and the canyons of the ocean.
- **Solar System Simulator** – From NASA
- **Solar System** – A virtual solar system from National Geographic
- **Build a Solar System**
- **The Interactive Library** – This EdInformatics.com site is a list of links to interactive earth and space science sites. Some Java applets are standalone, and some come with lesson plans and notes
- **UCLA Physics and Astronomy Lecture Demonstrations**
- **Y Science Laboratories** – Realistic and sophisticated simulations covering chemistry, physics and planetary motion, from Brigham Young University

Biology labs

- **McGraw-Hill Biology Virtual Laboratory Exercises**

- **Learn Genetics Virtual Lab** (University of Utah)

- **Virtual Lab Microbiology** -- "Medical laboratory science students can learn procedures online through viewing films and problem-solving in a virtual Biosafety Level 2 laboratory. The interactive process allows for the identification of X microorganisms."

- **The Interactive Library** – This EdInformatics.com site is a list of links to interactive biology sites. Some Java applets are standalone, and some come with lesson plans and notes
- **Johnson Explorations** – Online explorations from The McGraw-Hill Companies. Interactive simulations for high school biology classes. Alternate links: **1**, **2**
- **TryScience.com** – Variety of online experiments
- **The Biology Place: Classic Edition** – A free website appropriate for regular and advanced biology. The LabBench corresponds to the AP Biology Labs
- **ExploreLearning: Gizmos** – Online simulations
- **Wisc-Online Learning Objects**
- **Biology: Virtual Labs** – Appropriate for AP Biology and beyond
- **Virtual Labs** – Appropriate for AP Biology and beyond

- **Virtual Labs** – From HHMI's BioInteractive
- **Virtual Labs** -- "These Virtual Labs help students learn basic laboratory techniques and practice methods used by lab technicians and researchers in a variety of careers, using specific food science lab processes."

- **Biointeractive** -- "[F]ully interactive simulations in which students perform experiments, collect data, and answer questions to assess their understanding. The labs combine animations, illustrations, and videos to convey key information and engage students in the process of science."

- **Virtual Interactive Bacteriology Laboratory** (Michigan State University)

Anatomy, physiology and dissection

- See the list of **Anatomy Labs**

Microscopy, cells and microbiology

- **UD Virtual Compound Microscope** – A virtual microscope
- **The Virtual Microscope**
- **Virtual Scanning Electron Microscopy** – Interactive Java tutorials
- **Protista Tutorials** – Microscope views of organisms. Also shows rotifers.
- **A Virtual Pond Dip**
- **JayDoc HistoWeb** – From the University of Kansas Medical Center. A histology atlas that corresponds with the laboratory exercises of the Cell & Tissue Biology course

Genetics and DNA

- **Genetics Web Lab Directory** – Wide variety of genetics simulations and problems. Some are appropriate for middle school genetics; most are appropriate for high school genetics.
- **Genetics** – Some K-12 online labs
- **Virtual Peppered Moths**
- **DNA Restriction Digest and Gel Electrophoresis: A Virtual Lab**
- **DNA Extraction Virtual Lab**
- **The GEEE! in GENOME**
- **Learn.Genetics** - Genetic Science Learning Center
- **Engineer a Crop** – PBS interactive site where students can compare traditional and transgenic methods of selective breeding.

Health, medical treatment and blood types

- **Interactive Health Tutorials** – From U.S. National Library of Medicine
- **Medical Mysteries** – Solve medical mysteries while learning about diseases and their causes.
- **Blood Typing** – Interactive game where you can learn about blood types and also determine what type an accident victim needs for a transfusion.

Population biology and dynamics

- **Population Biology Simulations** – From the University of Connecticut. A few population genetics and population ecology simulations written in Java.
- **Population Growth and Balance**
- **Population Dynamics** – From MathCS.org

Animal behaviour, evolution and life science

- **The Animal Behavior Project** – At the University of Arizona
- **Life Science** – Interactive lessons from learningscience.com
- **Shedd Educational Adventures** – Marine life resources from the Shed Aquarium
- **Paleo Pursuit** – A game from The Virtual Museum of Canada
- **ENSI/SENSI** – Evolution and the Nature of Science Institutes
- **Illuminating Photosynthesis** – PBS interactive tutorial about photosynthesis; not a lab activity

The following biology laboratory simulations and educational learning exercises are available for a fee.

Commercial products

- **Biology Labs On-Line** – A series of 12 interactive, inquiry-based biology simulations and exercises
- **Late Nite Labs** – Includes both Biology and Chemistry labs.
- **TeqSmart Learning Objects: Science** – Includes interactive Animal Cell and Plant Cell exercises.
- **Biology LabPaqs** – Hands-on laboratory experiences

  MERLOT https://www.merlot.org/merlot/index.htm provides an enormous amount of online materials for science including virtual labs.

APPENDIX 2

Intuition Article

RESEARCH AND INSIGHT FROM THE FURTHER EDUCATION SECTOR

THE KNOWLEDGE

Remote learnings

The Covid-19 pandemic has seen virtual laboratories used more widely in a science setting, something **Dr Neil Peirson** was already investigating as a learning method. Here, he outlines the key findings of his research

In the 'new world' that a global pandemic is beginning to shape, it is very likely that we will rely much more on digital technologies. Viewed from within the event, the tendency is to adopt a perspective that focuses on the immediate. However, it is worth remembering that planning ways to move forward in uncertain times has always been a risky business, perhaps never more so than now.

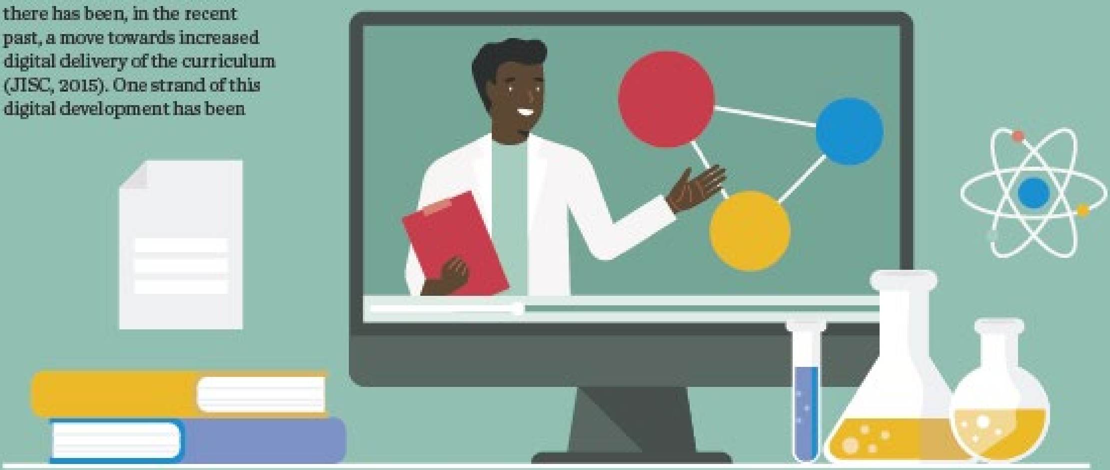
Education is an area where there has been, in the recent past, a move towards increased digital delivery of the curriculum (JISC, 2015). One strand of this digital development has been the emergence of the 'virtual science laboratory'; this has been particularly true in the context of higher education (HE) (Lewis, 2014).

Virtual laboratories (VL) have existed for a number of years and recently have increased in sophistication. These computer-based simulations can be quite simple or highly detailed representations of a real laboratory. They offer a good way for students to develop practical skills; Miller, Carver and Roy (2018) found no difference in outcomes compared with real laboratories. Some of the newest versions are based in virtual reality, making them feel even closer to the real laboratory (RL).

The context

This study is concerned with students at a large Midlands-based further education (FE) college and how they respond to the use of virtual laboratories. Following BTEC applied science programmes, our students are familiar with a 'normal' school or college science laboratory.

These students come with a wide range of experience; the majority coming from ethnic minority backgrounds, many are non-native English speakers. Often, they have previously been disappointed by low levels of attainment while at school. Many lack self-confidence



and resilience when faced with new challenges. The study is carried out in line with the latest British Educational Research Association (BERA) Ethical Guidelines for Educational Research (2018).

The questions

I started this project with a large number of questions. I have refined these down to three general questions:

- Does teaching practical science in a VL increase students' skills and understanding in the same way as in a physical laboratory?
- How do our students feel about learning practical science in a VL?
- Will our students develop the employability skills required by employers?

The method chosen for this study is a questionnaire. I decided to use the five outcomes (see table) identified by Holman (2017) in a study of practical science as a basis for questions about how effective the students found VL compared with RL. It might be argued that Holman's point 4 is vague, so it may not be clear what the student is thinking when answering.

There are two questions about each outcome; the first, on a five-point Likert scale, and the second, a more open question, inviting a text answer. Both questions address the comparison of experiments carried out in real laboratories with those in virtual laboratories.

The questionnaire was presented as an additional task after the completion of a virtual laboratory exercise similar to one undertaken in a real laboratory earlier in the year. This is not an ideal way to make the comparison, which may bias the results. However, under the circumstances of college closure, it was the best option available.

If we look at the results from a qualitative viewpoint, then we can hope to gain some useful insights.

The main benefits of practical science, Holman (2017)

1	To teach the principles of scientific inquiry
2	To improve understanding of theory through practical experience
3	To teach specific practical skills, such as measurement and observation, that may be useful in future study or employment
4	To motivate and engage students
5	To develop higher-level skills and attributes, such as communication, teamwork and perseverance

Following the work of van Maanen (see Connelly and Clandinin, 1990) we can concentrate on the verisimilitude of the comments rather than their validity in the strictest sense.

Results – what students say

There is a bias in the Likert data for all questions in favour of the RL, as shown in Figure 1; this is in contrast to the findings of Miller, Carver and Roy (2018), who conducted a similar study in an HE context. The bias appears most distinct for Q4, concerning motivation.

From the comments, it appears that one important factor is that of the social interaction involved in the RL. This resonates closely with the work of those who support a social-constructivist approach to learning. They emphasise the importance of learning as an interactive, social practice to argue that learning, as well as motivation, occurs as a result of the interaction of students in the physical environment.

Such interactions are (currently) difficult to replicate in the VL. Students recognise that to "actually do it physically" helps them to gain "understanding, using real practical experience". Students' responses in the study also show an appreciation of developing "good practice for future" as they "work as a team together", learning "better measurement and observation skills".

Many of the students found value in the VL. Some who "had trouble doing it in class... just sat and completed it and actually understood it". Learners also appreciated the benefits of opportunities offered in the VL for self-paced work: "I can also take my time to help me understand the theory" or "re-read pieces of information and gain a new understanding".

> “LEARNERS APPRECIATED THE BENEFITS OF OPPORTUNITIES OFFERED IN THE VL FOR SELF-PACED WORK

Responses indicate that students also found value in developing deeper learning "because I can use the simulations to help me understand how things work" and "virtual is good for the explaining". One student reported that the VL provided a refuge: "Doing experiments in a lab makes me nervous and panicked. I like doing them virtually." There is a safe space to try things out "and not mess it up", surrounded by others.

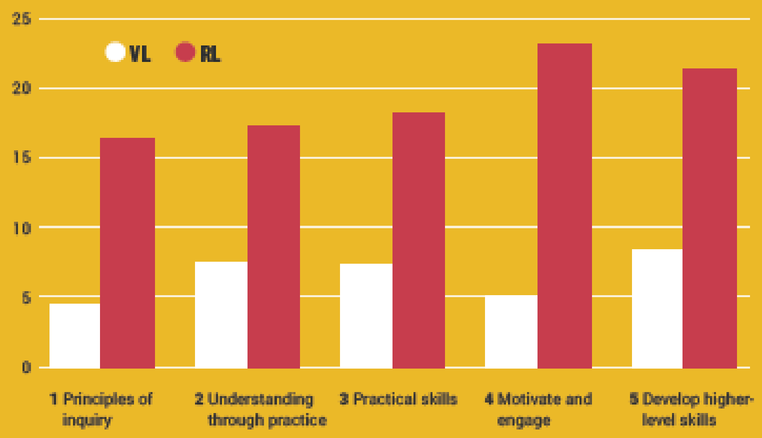
It may be useful here to draw out the following tentative findings:

- The VL is technology-dependent. Students using a range of devices have a range of experiences: meaning that unfamiliar software can lead to frustration →

DR NEIL PEIRSON is lecturer in chemistry, physics and applied science at The Sheffield College

Figure 1: What students say

The Likert data is shown in the figure below, where only the combined preferences for each type of laboratory are shown (a total of 34 responses; neutral omitted)



- During lockdown, some students may feel the desire to be in a physical laboratory as part of a desire for 'normality'
- Students may experience negative physical environments while completing VL work
- Data and comments suggest that students are concerned with the issue of 'motivation'; however, as discussed above, this urgently warrants clearer definition and further investigation
- Students' current language achievement may reduce the quality of their interaction with virtual laboratories and their willingness to make a written response.

The way forward...

From this limited study, it appears that careful implementation may be key to the success of VLs in FE. Students can be excited and engaged by new technology. However, difficult-to-use technology or software can cause issues.

While it would be inappropriate to make generalisations from a small-scale research study such as this, the following issues appear, in the use of VLs in the teaching and learning of practical science, to be worthy of more in-depth and sustained research as follows:

- There needs to be greater understanding of both the intellectual and emotional experiences of learning through VLs in order to make the most of these resources
- Care needs to be taken during the planned implementation of VLs in FE in order to explore how we can best employ VLs to enhance students' learning experiences
- Biggs (2015) argues that assessment and teaching should align with educational outcomes. In the context of VLs, the choice of technology, software and the explanatory language used need to be considered carefully, to ensure that these also align with the desired outcomes
- Outcomes should reflect the values that practical science can give in educating FE students. Those identified by Holman (2017), however, may not reflect those most relevant to FE students, particularly in relation to motivation
- The implementation of VLs needs to be monitored and studied systematically to allow careful reflection.

→ **This research was carried out as part of the Education and Training Foundation's Practitioner Research Programme with the Centre for Excellence in Teacher Training at the University of Sunderland (SUNCETT). Many thanks to Maggie Gregson, professor of vocational education and director of SUNCETT, for her support with this article**

References and further reading

Biggs J. (2015) *Aligning teaching for constructing learning.*

British Educational Research Association [BERA]. (2018) *Ethical Guidelines for Educational Research* (fourth edition). London.

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Lewis D. (2014) *The pedagogical benefits and pitfalls of virtual tools for teaching and learning laboratory practices in the biological sciences.* The HE Academy.

Miller TA, Carver JS and Roy A. (2018) To go virtual or not to go virtual, that is the question: a comparative study of face-to-face versus virtual laboratories in a physical science course. *Journal of College Science Teaching* 48(2): 59.

APPENDIX 3

Consent and information forms

PARTICIPANT CONSENT

Project:

Lived Experiences of Science Education: explorations of virtual and actual science laboratories in Further Education

I... voluntarily agree to participate in this research study.

I have read and understood the attached study information and, by signing below, I consent to participate in this study.

I understand that if I participate the time commitment is around 10 minutes to complete a questionnaire and possibly a further 30 minutes if I wish to engage in an interview or focus group.

I understand that I have the right to withdraw from the study without giving a reason at any time during the study itself.

I understand that I also have the right to change my mind about participating in the study for a period of two weeks from the collection of data.

I understand that if I do withdraw any data collected concerning me will be immediately destroyed.

Signature of research participant

-- ----------------

Signature of participant   Date:

Signature of Researcher: Neil Peirson

I **Neil Peirson** believe the participant is giving informed consent to participate in this study

Research Project Date: December 2021 – December 2023

Participant Information Sheet

[redacted]

1. Research Project Title

Lived Experiences of Science Education: explorations of virtual and actual science laboratories in Further Education

2. Invitation

You are being invited to take part in this research project. Before you decide to do so, it is important you understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part. Thank you for reading this.

3. What is the project's purpose?

This research project aims to investigate the effectiveness of virtual laboratories in further education.

4. Why have I been chosen?

You have been chosen because you teach a science subject at the college and you are involved in laboratory based teaching and learning activities.

5. Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part you will be able to keep a copy of this information sheet and you should indicate your agreement to the online consent form. You can withdraw at any time during the study and for two weeks from the collection of data. You do not have to give a reason. If you do withdraw any data you have provided will be destroyed immediately.

6. What will happen to me if I take part?

You may be asked to participate in a questionnaire, a focus group or an interview based on your experiences of science, in particular, practical science both real and virtual.

It is anticipated that the questionnaire will take 10 minutes to complete and that if you are involved in an interview or focus group this would require approximately a further 30 minutes.

7. What do I have to do?

If you wish to participate you will contribute to a questionnaire, focus group or interview. There are no other commitments or lifestyle restrictions associated with participating.

8. What are the possible disadvantages and risks of taking part?

Participating in the research is not anticipated to cause you any disadvantages or discomfort. The potential physical harm or distress will be the same as any experienced in everyday life.

9. What are the possible benefits of taking part?

A possible benefit to participating in this study could be a better understanding of the virtual laboratory activities and how they inform your learning.

10. What happens if the research study stops earlier than expected?

Should the research stop earlier than planned and you are affected in any way we will tell you and explain why.

11. What if something goes wrong?

If you change your mind about participation, please contact me by email to cancel your participation. If you feel unhappy about the conduct of the study, please contact me immediately or the Chairperson of the University of Sunderland Research Ethics Group, whose contact details are given below.

12. Will my taking part in this project be kept confidential?

All the information that we collect about you during the course of the research will be kept strictly confidential. You will not be able to be identified or identifiable in any reports or publications. Your institution will also not be identified or identifiable. Any data collected about you in the questionnaire will be stored online in a form protected by passwords and other relevant security processes and technologies.

Data collected may be shared in an anonymised form to allow reuse by the research team and other third parties.

13. Will I be recorded, and how will the recorded media be used?

Your responses to any questionnaire will be recorded electronically. Participation in focus groups and interviews will be recorded by written notes and by audio recording, to facilitate note taking. No audio recordings will be used further without specific written consent. Field notes will be taken during the research but will not contain any identifiable information.

14. What type of information will be sought from me and why is the collection of this information relevant for achieving the research project's objectives?

The questionnaire will ask you about your experience and opinions of using real and virtual laboratories. These may be explored in personal interviews or in focus groups.

15. What will happen to the results of the research project?

Results of the research will be published. You will not be identified in any report or publication. Your institution will not be identified in any report or publication. If you wish to be given a copy of any reports resulting from the research, please ask us to put you on our circulation list.

16. Who is organising and funding the research?

The project is a partnership with Sunderland University and the Education and Training Foundation. The research supervisor for this project is Dr Michael Smith, University of Sunderland (michael.smith@sunderland.ac.uk)

17. Who has reviewed the study?

The University of Sunderland Research Ethics Group has reviewed and approved the study.

18. Contacts for further information

Dr Neil Peirson, mailto:

Dr John Fulton (Chair of the University of Sunderland Research Ethics Group, University of Sunderland)
Email: john.fulton@sunderland.ac.uk Phone: 0191 515 2529

Thank you for taking part in this research.

Neil Peirson Lecturer in Chemistry, Physics and Applied Science
MPhil in Educational Research student (Sunderland University)

APPENDIX 4

Ethical Approval (Sunderland)

Section D: About the participants

1. Potential Participants

Participants will be learners drawn from the groups I teach. All will be over 16, most will be over 17 and a significant number over 18. Any staff who participate will be colleagues from within my College.

2. Recruiting Potential Participants

Participants will be recruited using an email to give them the relevant information. They will be informed of the importance of their participation and assured of their anonymity. The study will be carried out in accordance with the BERA guidelines and GDPR Act.

3. Consent

Will informed consent be obtained from the participants? (i.e. the proposed process) Yes

Participants will be provided with an information sheet and asked for consent using a form similar to that attached in section F.

4. Payment

Will financial/in kind payments be offered to participants? No

5. Potential Harm to Participants

What is the potential for physical and/or psychological harm/distress to the participants?

None

How will this be managed to ensure appropriate protection and well-being of the participants?

N/A

Section E: About the data

1. Data Confidentiality Measures

All data will used and stored in accordance with BERA2018 Guidelines and GDPR Compliance 2018. Data will be used and stored anonymously.

2. Data Storage

I will personally collect and analyse the data. Any audio recordings will have participants consent and will only be used to facilitate the production of transcripts. All data will used and stored in accordance with BERA2018 Guidelines and GDPR Compliance 2018. Data will be used and stored anonymously.

Section F: Supporting documentation

Information & Consent

Participant information sheets relevant to project?
Yes

Document 1015420 [Add new version]
Information Sheet

- Version1 (Information_sheet.docx)
- Version2 (Information_sheet_staff.docx)
- Version3 (Information_sheet_student.docx)

+ Click to add a participant information sheet

Consent forms relevant to project?
Yes

Document 1019928 [Add new version]

- Version1 (Consent_form_staff.docx)

Document 1015421 [Add new version]

- Version1 (Consent_form.docx)
- Version2 (Consent_form_student.docx)

+ Click to add a consent form

Additional Documentation

Document 1019930 [Add new version]
Example questions for staff

- Version1 (Questions_for_staff.docx)

Document 1019929 [Add new version]
Example questions for students

- Version1 (Questions_for_students.docx)

+ Click to add an additional document

External Documentation

- not entered -

Section G: Declaration

Signed by:
Neil Pearson

Date signed:
Sat 2 April 2022 at 13:43

Offical notes

- not entered -

Final Decision on Application

Approved

Additional supervisor comments

- not entered -

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APPENDIX 5

Ethical Approval (College)

These documents have been redacted to remove names and references to the institution where the research was carried out.

These are the documents about ethical approval for the project form the University of Sunderland.
I hope you do not have any issues, please let me know if you would like any clarification.

Thanks

Neil

Dr Neil Peirson
Lecturer in Chemistry, Physics and Applied Science,

Hi Neil,

I cannot see an issue with your request, the students will give their consent and will be aware of the purpose of the study. Best of luck with the study.

Best wishes,

APPENDIX 6

Example student/staff survey

Your experiences of Virtual Laboratories

This questionnaire asks you about your experience using both physical (real) and virtual laboratories. You will be asked to agree or disagree with a statement and then you have space to comment about the statement. When answering the questions think about your recent experiences in both the physical and virtual laboratories. (C2B)

neil.peirson@sheffcol.ac.uk Switch accounts

Not shared

* Indicates required question

Why do you like science?

Your answer

Have you used an animation, simulation or virtula laboratory to investigate experiments (tick any you have used)

- [ ] simulation
- [ ] virtual laboratory
- [ ] animation

How do you normally access the animations / simulations / virtual laboratory

- ○ PC or laptop
- ○ I phone
- ○ Android phone
- ○ other smart phone
- ○ Chrome book
- ○ Another device

If you have used more than one type of device, do you get a different experience?

Your answer

Thinking about you experiences with animations / simulations / virtual laboratories; do you learn more about the principles of scientific inquiry from these than from physical laboratories.

	1	2	3	4	5	
Strongly Agree	○	○	○	○	○	Strongly Disagree

Do you think you learn more about the principles of scientific inquiry from animations / simulations / virtual laboratories rather than physical laboratories?

Your answer

I gain more of an understanding of theory through practical experience using real rather than animations / simulations / virtual laboratories.

	1	2	3	4	5	
Strongly Agree	○	○	○	○	○	Strongly Disagree

Do you think you gain more understanding of theory through practical experience using real or animations / simulations / virtual laboratories?

Your answer

Virtual laboratories teach me more practical skills, such as measurement and observation, than I learn in a physical laboratory.

	1	2	3	4	5	
Strongly Agree	○	○	○	○	○	Strongly Disagree

Do you think virtual laboratories teach you more practical skills, such as measurement and observation, than you learn in a physical laboratory?

Your answer

I feel more motivated and engaged using a physical laboratory rather than a virtual laboratory.

	1	2	3	4	5	
Strongly Agree	○	○	○	○	○	Strongly Disagree

Do you feel more motivated and engaged using a physical laboratory rather than a virtual laboratory?

Your answer

I develop higher level skills and attributes, such as, communication, teamwork and perseverance; when using a virtual laboratory rather than a physical laboratory.

	1	2	3	4	5	
Strongly Agree	○	○	○	○	○	Strongly Disagree

Do you feel you develop higher level skills and attributes, such as, communication, teamwork and perseverance; when using a virtual laboratory rather than a physical laboratory?

Your answer

Are you happy to contribute to future research? Please add you name if you are willing to discuss your views. Thanks. *

Your answer

Submit

Clear form

APPENDIX 7

Example student/staff interview scripts

Examples of interview questions asked to students:

Why do you like science?

Have you used an animation, simulation or virtual laboratory to investigate experiments?

How have you normally access the animations / simulations / virtual laboratory?

If you have used more than one type of device, do you get a different experience?

1. *students experience learning in a virtual laboratory as a mirror of reality?*

How real does the Virtual Laboratory feel to you?

When you do things in the virtual laboratory does it remind you of what you have done in the real laboratory?

What about something which is new to you?

Do you think about the virtual laboratory experiments when you are back in the real laboratory?

2. *students regard the results of experiments conducted in that environment as trustworthy?*

Do you believe the results given by an experiment in the virtual laboratory?

Why?

Do you believe the results given by an experiment in the real laboratory?

Why?

What if they are not the same?

3. *teachers can have confidence in the educational value of learning in virtual laboratory?*

Are you more motivated when using a physical laboratory or a virtual laboratory?

Why?

Which skills do you feel you learn from practical science?

Do you feel these skills are generated differently in a digital environment?

Why?

Do you think about things differently in the real or virtual laboratory?

Why?

- Does the virtual world provide the same cognitive development to that gained by the normal process of physical experimentation?

Do you think you learn more about the principles of scientific inquiry from animations / simulations / virtual laboratories rather than physical laboratories?

Do you think you gain more understanding of theory through practical experience using real or animations / simulations / virtual laboratories?

Virtual laboratories teach me more practical skills, such as measurement and observation, than I learn in a physical laboratory.

Do you think virtual laboratories teach you more practical skills, such as measurement and observation, than you learn in a physical laboratory?

How do students view learning in the virtual laboratory? Can we develop a method of implementation aligned with the desired learning outcomes (Biggs and Tang, 2011)?

Example of the questions asked to staff:

Why do you like teaching science?

Have you used an animation, simulation or virtual laboratory as part of your teaching?

How do you normally use these animations / simulations / virtual laboratory?

Do you find students respond in different ways depending on how they access these applications?

Do you think students learn more about the principles of scientific inquiry from virtual or physical laboratories? Why do you think this is?

Do you think students gain more understanding of theory through practical experience using real or animations / simulations / virtual laboratories? Why do you think this is?

Do you think virtual laboratories teach students more practical skills, such as measurement and observation, than they learn in a physical laboratory? Could you say why you think this might be the case?

Do you think students feel more motivated and engaged using a physical laboratory rather than a virtual laboratory? Again, why do you think this the case?

Do you think students develop higher level skills and attributes, such as, communication, teamwork and perseverance, when using a virtual laboratory rather than a physical laboratory? Why do you think this?

Do you have an overall impression of how students learn using animations / simulations / virtual laboratories?

Do you feel animations / simulations / virtual laboratories are a useful addition to teaching and learning? Why do you have this view?

APPENDIX 8

T1. Hands-on / Reality

STUDENT G: *Although I enjoy the theory side of science. I feel like having the practical side of it makes it feel more, it makes it feel more real and it makes it feel more, I don't know the word, like enjoyable.*

STUDENT F: *yeah. I am a hands-on learner.*

STUDENT G: *Yeah.*

STUDENT F: *See, I would rather do that with the theory cos it helps me learn the theory type in a way. So, I, I like the hands-on approach. I, I always have throughout like,*

STUDENT G: *yeah, I guess it's like if you ask a chef to learn to be a chef without cooking, it's like, because science is so hands-on, it relates to everything around you not applying that and not actually going through that yourself.*

The students feel that practical science is an essential part of their learning, fundamental to their learning. One now asks:

STUDENT G: *Would you actually be a scientist?*

STUDENT F: *Yeah.*

STUDENT G: *Because although you know the theory, you can't apply it. It's like if it's like doing your driving theory test doesn't mean you can drive*

STUDENT F: *literally,*

STUDENT F: *literally*

STUDENT G: *you know what I mean?*

STUDENT G: *You could get full marks on that, but you can sit in a car and not know how to drive. I kind of think it's like,*

STUDENT F: *see, so you could explain the whole of chemistry, but you can't*

STUDENT G: *Exactly.*

STUDENT F: *You can't do it.*

STUDENT G: *If someone said like, do a reflux, you could tell 'em the whole. Like step-by-step routine of how you do it. You give them a, like a Quick-Fit set and they look at it and they go, how do I stand it up?*

These students feel that without the embodiment of their knowledge in practical activity, the theory they learn is of no use. The question then is can they learn this in the VL. Do they feel that the activities in the VL feel real?

STUDENT A: *I think with the virtual labs, you're literally just dragging and dropping something and just moving things around on a screen. Whereas in real life, you literally have it in your hands to, to do, I think it's more engaging.*

INTERVIEWER: *… when you see a virtual laboratory … how real does it feel?*

STUDENT F: *I guess it doesn't … obviously you don't have the hands-on approach, so it doesn't feel like, oh, I'm in the lab type of thing… But I think it's quite nice because … if you actually in a lab you might go a little bit over when you're measuring things, but that's got be really precise*

STUDENT G: *yeah, I agree with that. I think it definitely doesn't feel quite the same. It's not going to because obviously you're just looking at it kind of one dimension … It's not got the, you're not picking things up yourself, finding which one is. It kind of directs you to things I think more…*

These students do not feel the VL is real – they are very aware of the different experience. So how is it different?

INTERVIEWER: *… When you're doing [it] in the virtual laboratory. What's really happening?*

STUDENT A: *I mean, technically nothing. It's just that.*

STUDENT B: *Yeah.*

STUDENT A: *And you are just, you're just running it, so it's not, it's not actually there,*

STUDENT B: *That's why its virtual*

STUDENT A: *so well, exactly. Just another screen tool.*

STUDENT G*: … With an actual, like a practical lab because it's a lot more hands on. You know, you're getting the equipment yourself. It, it takes longer. It feels a lot more like you're actually doing it. Whereas the virtual one, I think's just always a bit, it does feel like you're doing it, but it's nowhere near got the, the feel of the actual lab.*

The students seem to be particularly aware of the reality of touch.

STUDENT B: *Because the virtual one you're sat there staring at a screen… [but in the real one you are] like touching, touching stuff, like it is all connected to your brain. So, it kinda triggers like, oh, I know what that is – type of thing. Where if you just touching, like, just the keyboard, then it's just like – that's all.*

They feel a deeper connection through touch; it means more than '*just looking at a screen' (**STUDENT A**).*

STUDENT F: *Like in the normal lab … you can hold onto it…on the virtual lab you can't do that… I kind of like the hands on…you can like touch it.*

STUDENT G: *It's actually there.*

STUDENT F: *Yeah.*

STUDENT G: *It's actually. I know you know it's real, but it's actually, you've got it. I dunno how to explain it.*

STUDENT F: *I guess like results as well, you can actually [there] watching the screen*

STUDENT G: *Yeah.*

STUDENT F: *So, your results are there.*

STUDENT G: *You are writing it down.*

STUDENT F: *Yeah.*

STUDENT G: *You are taking note. You are measuring it; you're taking note of it from something you've set up.*

STUDENT F: *Yeah,*

STUDENT G: *I think it in that way it makes it [real].*

These students feel they have experienced a process, a pattern which embeds them in their learning.

Student C describes the different experiences like this:

INTERVIEWER: *Why would you prefer the real one?*

STUDENT C: *I like seeing things in my own eyes. It's kind of like, I don't know. The best way to describe this is reading a book and reading an eBook, reading an actual book is cooler.… it's just more accurate in that to just see what's in front of me.*

INTERVIEWER: *So is it, is it seeing, or is, is there touch involved or, or sound or,*

STUDENT C: *I mean all of them, all of those senses …*

… I prefer that to just clicking. I think it's better in terms of concentrating, no pun intended. Uh, I mean, my concentration levels in the actual lab are way higher than when I'm just scrolling mindlessly and clicking mindlessly in a virtual lab.

… It screens, I mean, it's good that the resources are there, but I think avoid screens.

For this student the VL does not seem real – it lacks depth and is superficial. The interactions with the computer (or phone) are limited to just a screen and a mouse.

It is similar for …

STUDENT D: *… [the real laboratory is] engaging you, like, completely with your skills, with your studies, practical, and even physically you are more engaged. But in virtual one is you are just sitting down and try to mix, combine everything.*

…*the practical one … you see all the process in front of your eyes, so even you can feel the temperature, you can see the colour change, everything from closely, but so we mainly think about the reason about the reactions, what's happening; but in virtual one is less realistic, so maybe you don't think about all the details. So, I think in practical, it's more in detail when you think about the experiment.*

… *it's engaging you completely like all your sense, and you feel more confidence when you do the experiment, when you finish because you feel you learned all this and you saw the experiment, so give you more confidence.*

The practical experience is also…

*(****STUDENT A****) … good for exams because if I have a question that links to a practical we've done, then my mind goes back to doing that practical I can remember… [but VL] like we've said, it's just another screen.*

STUDENT B*: Also, it teaches people health and safety, like general health and safety.*

INTERVIEWER: *Right. But you could, you could learn health and safety from a computer, couldn't you?*

STUDENT A*: It's not, it's not gonna affect you though. Let's say, um, something really, really bad happens in a lab. Oh. [In the VL] like you are just looking at a screen, you're like, well, that's not, that's not bothering me.*

Um, yeah. I mean, in our labs there's tons of other people in there as well, so you've got to be careful about being with around other people, making sure everyone else knows what's going on. Um, and then if you are doing a virtual one, a lot of the times the steps are just on screen, and you just have to – right – I need to move this to here and I need to mix that with that.

And I feel like when you're doing it in a lab as well, you have to think, well, I mean, you could probably do it on there [the VL] as well. Like … why am I using this? Or what happens? So, I think some things are similar – like the chemistry, but I feel like the personal aspect is definitely a lot different.

So, the student feels there is a lack of risk in the real laboratory, which does not exist in the VL; this runs through the students' responses and is identified as a separate theme, discussed below. For now, we can see that the feeling of risk is part of what makes the real laboratory feel 'real', while things in the VL are 'not bothering me'.

INTERVIEWER: *… when you're doing it virtually, do you, do you think back to what you've done in the real laboratory? Do you compare the two?*

STUDENT E*: I would say you do think about the process you experience in your mind. You experience doing the same motion pouring the substance, but there is a difference between doing it in real life and doing it [virtually], you don't really use the same skills. You don't practice the skills that you use in real life… it's mainly the manual dexterity part of it, you don't practice that…You do still practice your problem-solving skills though. So that's, quite similar, you still have to go through the motions and do the processes… I'd say the theoretical part is still there. It's just the practical side [which is missing].*

INTERVIEWER: *… if you're in the virtual laboratory and you come across something that you've not done in the real laboratory before, something that's new to you, how, how do you feel about that?*

STUDENT E*: I would actually say that better.*

You can practice it, get it wrong a couple of times, and then if you were to do it in the real world after you have some experience and some knowledge.

So, I'd say that's probably what I would like to use virtual laboratories.

INTERVIEWER: *… in the virtual laboratory… does it always make sense when you're looking at it?*

STUDENT E*: No, it is confusing sometimes. Okay. Uh, for example, if you dunno what the reaction is … it's confusing. Or if it's a new substance I've never used before, it's confusing and usually I'll do some research or try to understand looking, [in] a book or try to find in some reactions … It can be confusing.*

INTERVIEWER: *Is that different when you're doing it in the real laboratory?*

STUDENT E*: To be fair, it can be confusing in the real laboratory as well. I guess it's the same … you could ask somebody or look it up. It can be confusing in, in both places, although in virtual laboratory sometimes there is videos to help you direct to the, to the reaction, so that's quite helpful.*

The physical presence in the laboratory can involve particular actions and clothing not normally found outside the laboratory …

STUDENT *G*: *Yeah. Like it feels more like rewarding when you do it practically,*

STUDENT F: *I guess in a way. Like you feel, I don't wanna say it like, like a scientist.*

STUDENT G: *It feels real … it feels more like, like when you think about, oh, I'm gonna do A level science. When you, like in year 11, you think I'm gonna wear a lab coat and I'm gonna do all these practicals. It feels more fulfilling to do it in person rather than – like you, you could literally be sat at home in bed doing the virtual one that's not, don't feel it doesn't quite feel as rewarding.*

STUDENT F: *in other words, you just like wearing a lab coat.*

STUDENT G: *Yeah. We like the goggles and the lab coat like tie me hair up, light the Bunsen burner. It feels, it feels nicer… It makes it more real in your head … I'm putting on this lab coat, people around me are gonna think I know what I'm doing, so let's make it look like I know what I'm doing. Let's do it right. Let's do it. Let's get the results I want.*

STUDENT F: *I guess like I don't want to talk psychology, but [it] is that authority*.

STUDENT G: *Yeah,*

STUDENT F: *bit like … a uniform, I guess.*

STUDENT G: *Yeah,*

STUDENT F: *it's a bit like, I dunno, you always like stereotype – the goggles and the lab coat. I think it's kind of nice to, like, you'd be able to put it on and be like, ooo,*

STUDENT G: *… you put it on, you[r] like, yeah, I am a scientist.*

STUDENT F: *you feel more ready…*

INTERVIEWER: *… if you were doing science and you didn't do any practicals, did you feel like you were missing out on something?*

STUDENT F: *Yes.*

STUDENT G: *Yeah … I don't think it'd feel as fun …*

APPENDIX 9

T2. Doing it myself / Control

STUDENT F: *… we did a practical the other day where we made aspirin… I went home and told my mother I've just made aspirin.*

For this student there was a sense of achievement in making something themselves (in the real laboratory).

However, the VL does not always allow students to feel engaged in learning…

STUDENT A: *… it's helpful in some ways of … explaining how to do an experiment, but sometimes it kind of like does it for you. So, you kind of just sitting there and watch[ing], so it doesn't always go in.*

Also, with the VL …

STUDENT A: *…because it's all very precise. Like you can only do the certain measurements or it's like I put 10 millilitres in of this into a measurement cylinder, then you know that it is exactly that.*

STUDENT B: *If you do it yourself on the virtual lab and you put 15 in, it'll say that it's incorrect. So, it kinda corrects ya*

However, for the real laboratory…

STUDENT B: *I think it engages like your brain more … they say a lot within our generation is that a lot of people aren't engaged cause they're just staring at screen. So, I think anyway, … you shouldn't stop doing things in real life 'cause then everything will just turn [into] staring at screen[s].*

STUDENT C: *… it is easy to control the measurements and just how, we take data and things like that … in terms of studying, I just prefer … the physical lab because it's easier to understand how things actually work and how to control things better… I gain more skills through the physical life… it feels [when] actually doing the experiment [I am] more in control … it's easier to see how things are actually being done.*

STUDENT E: *… because I have control over it from the beginning to end. I have control over deciding which apparatus to use, which reactants to use.*

However, sometimes there is less of a difference…

STUDENT C: *… in the real laboratory, if I'm doing something and I have it in front of me, then I'm just gonna follow the steps and do it as accurately as I can, so I can get the right results; in the virtual laboratory – same – but if I don't get it, it kind of guides you through it.*

Also, there are some advantages to using the VL, if you want to check something…

STUDENT F: *… you don't actually have to get everything back out again. It's just simpler.*

STUDENT G: *I think also like if you know that there's a little bit you've forgotten, it's much easier than doing the practical again to just quickly hop on a computer or your phone, carry it out, and then it's back in your head.*

STUDENT F: *… [if] such like covid happens again, I think they're a good way, cuz obviously home learning, we can't set a lab up at home. I think it's handy to have that source. It's a source that's there, so it's not - lab or nothing - it's a lab or this, it kind of gives it, a like, a backup in a way… we did the practical, but we can also like kind of redo [it] at home. I do like that. A sense that I know that, yeah, I might have done it a few months ago, but I can go and do it at home whenever I want. I think it's good.*

STUDENT G: *… I think it's like nice to know it's there if you need it. Like say, you did the practical and you … weren't quite sure on it, you can then use that to kind of solidify it.*

However, students wonder who is actually in control of their learning in the VL…

STUDENT G: *I think I'm a bit like, would I have actually got that in a real thing? I think it's cause. Quite a lot of the times because it feels like they direct you somewhere. They want you to do it right eventually so you can then do all the calculations and everything. I feel like sometimes it's a bit like, would I actually have got that? Would I not have? I dunno, sometimes I'm a bit unsure*.

STUDENT F: *I feel that, especially with doing the actual practical, I think sometimes getting [it] wrong and getting the wrong results is kind of good in a way… So, then you learn from it next time. But … I know what you mean, just like push[ing] [you] towards getting the right answer.*

They feel that they have some control in the real laboratory which helps build their skills…

STUDENT F: *…I just like the fact that when we do… them by yourself … I guess it's the thing of taking, like, the leader role… and being like, right. I'm going to think … follow instructions. I know I'm quite thinking, I like tick it off. Yeah. I think I'd being more organized, making sure your equipment's in the right area. You're not having to go an' get the same thing as you used before. You don't have to get another pipette or anything…That has always been like really organized.*

STUDENT G: *I don't think you tend to actually learn the skill fully with a virtual lab. I think it's more you're seeing it happen, but I don't think you're learning it yourself. I think that's got to then be reinforced by like practical labs … with like multitasking and being organized and stuff, there's not really any way to do that over a virtual lab. It kind of goes through in in the most like, efficient way …. It tells you what to do, as you're doing it. So, I feel like you don't have to apply as much to it… Rather than … just saying, I did it right. I could do it wrong and then do it right.*

APPENDIX 10

T3. Method / Skills

INTERVIEWER: *So which skills do you think you learn from practicals?*

STUDENT C: *a lot... First, understanding the steps and maybe doing things more carefully and accurately, like measuring something or when having to repeat a process; knowing how to put the data in a graph…*

and for…

STUDENT D: *… Many skills … mostly safeties, Hazards, … end pointing of the acid and the base … you read it in theory and practically again, … measuring also… how to use your hands to process the experiments, so like [making] measurement.*

Students feel that the VL is useful as an introduction to a practical…

STUDENT A: *… if you've never done chemistry before and you want you to do an experiment, and if you're in a lab, it's like, right, I need to get these, these, these. What happens if something goes wrong? But at least with [the VL], everything is already there for you to have … a smooth practical before you do it in a lab. I think it's a good, doing virtual labs is a good reminder for practical.*

STUDENT B: *It usually explains it quite well … there's usually, step by step how to do it. So, I think it's quite good… if you have no idea what you're doing, like even if you've never done chemistry before, you probably understand.*

The VL helps with the method, developing a step-by-step approach…

STUDENT A: *…I think … doing virtual labs is a good reminder for practical… with the titration, especially with the Royal Society of Chemistry one, it goes through the calculations as well. So, [if] … you weren't sure of how to calculate, whatever you need … then going through it … step by step for a calculation to do [with] your own results … that helps.*

STUDENT C: *… mostly with titrations, it helped me a lot [to] remember the process and the calculations that we had to do; especially with the mean titre thing.*

STUDENT C: *… but also when we were doing the swirling methods. That's mostly where I struggle. But it helps me retrace the steps without having to read the paper as much or asking [another student] what's going on … every 20 seconds… in the virtual laboratory… it kind of guides you through it… is it more in terms of understanding the practical and just going through it in order to get it…*

STUDENT B: *…but it's more of the actual how to do the practical that helps … cause like you might forget to do something like, I don't know, rinse the burette out or something like that. So, it's like human error.*

… the VL reminds you – it does not forget. It can also teach you new ways…

STUDENT D: *… sometimes you learn some tips … I remember it was like [cleaning the] pipette, how to rinse it … we used to do it differently … but in the virtual lab it was different … fill it with the liquid, and then … pour it again and use it again, so, it was different. So sometimes you get some tips…*

STUDENT D: *… sometimes … you don't have access to all these things, so still it's a chance to … work on it in [the] virtual [laboratory].*

However, there are some skills the students feel the VL is less good at teaching…

STUDENT A: *… with a real lab, you actually learn teamwork skills as well … like communication. Whereas, if you're just doing it individually, you're not gaining anything out of that, you're not talking to anyone or helping people out.*

STUDENT A: *… in our labs there's tons of other people in there as well, so you've got to be careful about being with around other people, making sure everyone else knows what's going on and then if you are doing a virtual one, a lot of the times the steps are just on screen and you just have to, right, I need to move this to here and I need to mix that with that.*

STUDENT C: *… in practical one, it's like skills, you gain it. But in virtual one, there is no skill, you just need to follow the process and know the theory … So, you don't gain any skill about like how to take exact measure from pipette or use dropper and all these things.*

INTERVIEWER: *… do you think there are differences?*

STUDENT D: *… some things … you cannot imagine them or … think about them unless you do it in practical ... Otherwise, [if] you want to learn them, you don't know the reasons of it.*

There is also a balance, both real and VL have benefits and can help students learn about methods and skills…

STUDENT C: *… in the virtual laboratory, if you make a mistake, it's easier, take it back. So, I do enjoy that… [and] the virtual laboratory is easier in terms of understanding things - mathematically. The physical laboratory is easier in terms of understanding how things actually work and how to use the equipment. I think that's a big one - how to actually use the equipment.*

INTERVIEWER*: … you're thinking about things in a different way to when you are doing the real experiment?*

STUDENT B: *Probably not different, … you just have to think more in the real one.*

STUDENT C: *… when I'm doing things or watching someone do it in an actual lesson, it's easier to understand because … I'm seeing how things are playing … out in front of me rather than just reading, reading, reading, reading, reading and watching a video and clicking buttons to see how things … work, but I would prefer to … do the virtual lab one first and then go to the lesson and see, oh, that's what's going on; that's how it became that colour…. I think the virtual laboratory is just better for preparation … seeing how things actually work in terms of maths and equations and what's going on with the particles.*

STUDENT E: *… you experience … the same emotional pouring the substance, but there is a difference between doing it in real life and doing it [virtually], you don't really use the same skills, you don't practice these skills that you use in real life … it's mainly the manual dexterity part of it - you don't practice that…*

INTERVIEWER: *… do the ideas come back from the virtual laboratory to the real laboratory?*

STUDENT D: *Yeah, like the steps and the stage, and sometime in virtual, it's like caption open and tells you why, why you do this, why you wait, and what you hit, and notes. So, you get some tips, and you can use them in real world… especially the steps, like which one you should do first and second. It's like … step by step…finish one step, you go to second one.*

INTERVIEWER: *… So, you think, oh I've done this before because I've done it virtually?*

STUDENT E: *Yeah, you definitely do. You, you remember you've done apply it, especially cuz you had repetition as well, you try a couple times … that is helpful.*

I think starting in a virtual laboratory is good. Help build knowledge and putting it, applying it in real life. That's the way I would see it to do it – the sequence of events.

What do students gain from using the VL first…

STUDENT E: *Firstly, just some basic knowledge on the topic. Just the introduction. Or maybe before the lesson, the teacher tells the students – look over this. Then I'd say virtual laboratory build[s] up the confidence, [you can] get to have many trials and then the … real part. I think that would be the morning off.*

INTERVIEWER: *… So, overall, do you think that virtual laboratories help you learn?*

STUDENT E: *… Yeah, I think it helps you learn, and it definitely helps you practice … [you] are practically able to do that easily, you usually have the comfort of your own home, set up quicker. It's a good value you get out of them.*

However, some prefer to use the VL after the real practical…

STUDENT F: *… I think it's a good way of testing what we already know. So, in a way, cuz obviously ask you questions, I think it's a good way to like recap what you've done.*

STUDENT G: *Yeah.*

STUDENT F: *So, you don't actually have to get everything back out again. It's just simpler.*

STUDENT G: *… I think also like if you know that there's a little bit you've forgotten, it's much easier than doing the practical again to just quickly hop on a computer or your phone, carry it out, and then it's back in your head.*

STUDENT F: *… cause then it's more … of [a] revision source in a way … So, you going through what you've already done, it's not necessarily learning, it's necessarily recapping what you've already done.*

STUDENT G: *… Yeah. I think you tend to pick up more with an actual … practical lab because it's a lot more hands on…Whereas the virtual one, I think [it] … just kind of tops up what you've already learned.*

The VL can help with improving experimental techniques…

STUDENT F: *… if we do something wrong on the virtual, you kind of remember it to do it … when you're doing the actual practical – which think it's quite nice.*

STUDENT G: *… Yeah. Like the pop-ups when it says like, oh, you've done this wrong try again, I think that helps you like pick up on it more.*

STUDENT F: *… I always remember doing [titrations] … I did not take the funnel out the top … So [now] I always remember take it out the top. I think [of] that always.*

STUDENT G: *… mine was … I read … the meniscus from the top and … [I] knew I had to do that, but I did it wrong … Now every time I do an actual practical lab, it makes me think back to it and I think from the bottom.*

I think [VLs] just help … clean up little things you do wrong; little things you wouldn't necessarily pick up when you're doing it yourself.

What about skills in the real laboratory …

STUDENT G: *… I think like kind of patience ... it is knowing that like if you get through that you will get to the end result. I think it teaches you a lot about patience, but also like multitasking. You need to … be getting equipment out and measuring everything or putting things like in the reflux while you're sorting out the part for next, like, step two… it does teach you a lot about kind of organizing yourself … to be able to do multiple things at once and not missing anything.*

STUDENT F: *… it's all things are gonna take into later life … you're still gonna have to be organized, you're still gonna have to work [in a] team so follow a leader at some point.*

INTERVIEWER: *… what about the results that you get in the real laboratory?*

STUDENT D: *… we could make mistakes… Like [for measuring the] concentrations in [a solution or] … taking the exact measures in the real world, but in the virtual is like [a] number, when you use this number, it … goes directly to the … calculator.*

Most students seem to prefer the real laboratory…

STUDENT D: *… Because it's engaging you, like, completely with your skills, with your studies, practical, and even physically you are more engaged. But in virtual one is you are just sitting down and try to mix, combine everything. But it's still helpful. It's like complementary.*

STUDENT F: *… I just like … taking … the leader role... think follow instructions ... tick it off … being more organized, making sure your equipment's in the right area … not having to go and get the same thing as you used before … like really organized.*

I would rather do [the real laboratory] with the theory cos it helps me learn the theory type in a way … I like the hands-on approach.

However, for the VL …

STUDENT F: *… you can't exactly go wrong in a way.*

STUDENT G: *… if you go wrong, you just knock a couple of points off … then you can carry on doing say like step two and three correctly … [but in the real laboratory] you put a lot more thought into it. You've gotta think, I need that. I need to be specific. So, I think it would build a lot more skills.*

APPENDIX 11

T4. Theory / Knowledge

Students say that the VL helps with learning …

STUDENT A: *… because you can physically see the theory behind an experiment like you can see the particles...*

STUDENT C: *… It helps in terms of learning things visually.*

STUDENT C: *… with titrations, it helped me a lot [to] remember the process and the calculations that we had to do. Especially with the mean titre thing … the virtual laboratory is easier in terms of understanding things mathematically.*

STUDENT F: *… I think it's a good way of testing what we already know … cuz obviously [it will] ask you questions, I think it's a good way to like recap what you've done.*

STUDENT E: *Processes … I would say the theoretical part is still there [for the VL]; it's just the practical side [missing].*

… *I feel like the learning will be slower … the links will be weaker [in the VL]; but this can't really be generalized because not every virtual laboratory is the same … From my experience, virtual laboratories help me when I already know the topic, it's just building the knowledge.*

INTERVIEWER: *… [do] you think differently in the real laboratory and the virtual laboratory? …*

STUDENT E: *I'd say they're, they're quite similar, cause you're still thinking about the reaction, you're still thinking about the same process that you know, or that you don't know if it's a new reaction. There is certain more aspects in real life, cognitive thinking of what you're actually doing with your hands, but I'd say it's quite similar.*

I think for a virtual laboratory to be really successful [it] has to integrate a lot of elements such as like colours or stuff that makes you remember … dunno exactly what the techniques are, but I think you remember because … you create links in real life. Like, I've done this, let's link to this.

And that's how you remember it. I feel like there needs to be an aspect of this in [the VL].

STUDENT G: *… but I think like using virtual labs more and more can be used for extra resources and extra revision and solidifying it.*

Some students find the physical laboratory is better for some aspects …

STUDENT C: *… The physical laboratory is easier in terms of understanding how things actually work.*

STUDENT D: *… if you see from closely … it's like better even for memorizing cause you saw … everything.*

STUDENT G: *… I think you tend to pick up more with an actual … practical lab.*

Although I enjoy the theory side of science. I feel like having the practical side of it makes it feel more, it makes it feel more real and it makes it feel more, I don't know the word, like enjoyable.

STUDENT F: *… I think one, they're like one of the like experiments we've actually done that think right? I get. It kind like solidifies the theory. So, you think Right, I know, I've just done the actual test. So, in the exam you think, oh, we've done this before. So, I can kind of like recall it. Which is obviously gonna be important.*

STUDENT G: *… I think it's good cause like obviously doing theory, you just kind of got the words in your head and sometimes it can get a bit mixed up. So, when it comes to an exam … you're not quite sure how to say something, but you've seen it, you know what it is, so you can then describe it in a way that's might not necessarily be the way it's written in the textbook, but it can still get you marks.*

APPENDIX 12

T5. Trust / Truth

For questions about trust and truth there seems to be a shift in the students views as they start to explore what they really do believe. The following is an example …

***INTERVIEWER:** how much you believe the results from the virtual laboratory?*

***STUDENT C:** As in that they're accurate?*

***INTERVIEWER:** Yeah.*

***STUDENT C:** Oh yeah. I say strongly believe.*

***INTERVIEWER:** Why do you believe that the results from the virtual laboratory are accurate?*

***STUDENT C:** I mean, from what I've done on the virtual laboratory, it's kind of this; this equals what's been happening on when we do the experiments. – Similar, also, I hope that was made by scientists, so it's accurate.*

***INTERVIEWER:** … why do you believe the results you get in the real laboratory?*

***STUDENT C:** Because I follow the right steps and compare results with the people and the virtual laboratory, and it seems accurate.*

***INTERVIEWER: …** if the result that you got from the virtual laboratory was this, and you got a very different result in the real laboratory, which one are you going to believe*

***STUDENT C:** first? I'm gonna [be very concerned] and then I'm gonna ask the teacher what's going on.*

But I would believe more the virtual laboratory just in case I did something wrong.

***INTERVIEWER:** Because you, you don't trust yourself to have done.*

***STUDENT C:** I mean, something could have happened, maybe the solution was too, dilute or something.*

***INTERVIEWER:** If you repeat the experiment with the real laboratory and you do it again, you do it really carefully and the result, you get the same result as you got last time?*

***STUDENT C:** then I trust my results,*

***INTERVIEWER:** Why do you now trust your results?*

***STUDENT C:** If I repeated it really carefully, then there's a high chance that I did right, so,*

but I'll also keep the virtual laboratory results in mind, just in case.

***INTERVIEWER:** … if there was a conflict? Which one would you believe most?*

***STUDENT C:** 70% … my results.*

The other students tended to show a similar pattern as they explored the ideas of trust in the real and VL.

They start with a greater trust in the VL…

***STUDENT E:** … I tend to believe it…*

STUDENT B: *… because it's from a trusted website that probably knows more than we do – well definitely than we do.*

… as long as it is from a trusted person or place, I feel like they've probably done the experiment more multiple times to actually [and] put it into a virtual lab to get the correct results…

STUDENT D: *… because it's been made by probably people who they had experience and experts, so probably they, they tried that experiment before, so they know and they expect what it should be - right, and we are just train[ing]. We train these ones, so probably make mistakes. That's why I believe virtual one is more reliable…*

INTERVIEWER: *… how would you judge reliability? …*

STUDENT D: *… It's from universities, probably or some professors or doctors*

STUDENT E: *… it's [from a] big website with credibility, then you're more likely to believe in scientific credibility especially if you are you're directed to by a teacher.*
if it's something …tangible ... it's something … you've seen.

STUDENT F: *… So, I'm guessing like, obviously they mean by people…*

STUDENT G: *… who've done,*

STUDENT F: *… done them, that know what they're doing, type of thing.*

STUDENT G: *… So, they're gonna be results, which [are reliable]*

STUDENT F: *… Or even they might have done the practical a few times before making them programs so we can use their results.*

STUDENT G: *… I guess the results should, like, make sense to what the practical is … Yeah. I guess you kinda trust them.*

INTERVIEWER: *Why? Why do you trust them?*

STUDENT F: *… guess they're coming. Well, we think they're coming from people who kind of been in the industry … They know what they're doing, type of thing.*

STUDENT G: *… I think it kinda comes down to, I don't know if it's like just around science, but I always think that like people who would make the programs or people who would input the information, what reason do they have for it to not be right? … You know what I mean? Like they, they have no reason to put wrong information in there. It wouldn't benefit them, and it wouldn't benefit us. So, I kinda in that way, I think actually I would trust them because why would they do it wrong? But then you never know.*

… what would be their game? Especially a scientist, you always wanna get the best end result. That's always what you want. What would they gain from putting wrong information in?

STUDENT F: *You seem to trust with it being like a thing as well, that's obviously been – probably – looked at and looked at again, you'd think people would pick up on it if they're bit like, well, I don't really agree with these results.*

STUDENT G: *I think if it was like completely wrong, I think it'd be obvious.*

STUDENT F: *Yeah.*

STUDENT G: *… You know what I mean? There's got to be some degree to where … if you were sat with us doing a virtual lab, you'd be able to pick up on it, if it was wrong.*

STUDENT F: *… I feel like … there'd be no point in making up and no would do to program, and then, yeah, what would be the point in making it?*

… because of the amount of research that must have gone into it. They can't just kind of make this program outta nowhere with things that aren't correct. I feel like it will be checked and checked again.

STUDENT G: *And I feel like virtual labs will probably be developed by scientists who've been doing it a lot of years. Whereas we are coming into this, we've probably never done the practical before … I guess I'd kind of trust that more, than what we're doing.*

However, they seem less sure of their own results …

STUDENT B: *… cause like you might forget to do something like, I don't know, rinse the burette out or something like that. So, it's like human error. That's the problem.*

STUDENT A: *… because it's us!*

STUDENT B: *… where we've only done it once. So, you could have an and how do you say it? an anomaly.*

Additionally, the trust in the VL is not complete…

STUDENT E: *I probably shouldn't just take it for granted, but I tend to believe it … there is aspects such as colour … of product which can vary in real life, so you're not too sure about that; or maybe the reaction is meant to fizz or bubble or have a vigorous reaction, you won't see that.*

STUDENT F: *I guess in a way … I don't … feel like you do trust them …*

STUDENT G: *I don't think I trust them as much as I probably should.*

STUDENT F: *Yeah.*

STUDENT G: *I think I'm a bit like, would I have actually got that in a real thing? I think it's cause, quite a lot of the times because it feels like they direct you somewhere. They want you to do it right eventually so you can then do all the calculations and everything. I feel like sometimes it's a bit like, would I actually have got that? Would I not have, I dunno. Sometimes I'm a bit unsure.*

Now if we test the trust …

INTERVIEWER: *You do an experiment in the virtual laboratory. You do an experiment in the real laboratory; the results are supposedly the same. They're not …*

STUDENT E: *which one do you believe. Good question - the virtual laboratory … Contrary to what I said.*

INTERVIEWER: *… Why do you believe the virtual laboratory?*

STUDENT E: *… it's probably been tested and if my teacher directed me to it, then I believe the teacher to be right.*

INTERVIEWER: *… so you believe the virtual laboratory … what would you then do?*

STUDENT E: *… I'd redo my real trial … Then if there is something different, again, I'll ask a couple of people.*

INTERVIEWER: *… you've run the virtual laboratory, you redo your real laboratory results, you repeat it maybe four or five times. You are getting the same result in the real laboratory, and it's different to the virtual laboratory. Which do you believe now?*

STUDENT E: *… I'm gonna be sure I've done something wrong then at that point, … something systematically wrong that I keep doing wrong … Maybe I keep adding the same concentration or something that I definitely ask somebody more knowledge for this, or maybe I'd assume that the program is wrong, and I've done the wrong reaction on the virtual laboratory.*

INTERVIEWER: *Okay. But you would believe that the system is right. It's something that you've done that's wrong.*

STUDENT E: *Yeah. I tend to, if the website's got credibility and the laboratory does, and I tend to believe that's right, or there's certain aspect I'm not seeing – for example, there's an ion and I think it's dichromate, which can be green, but sometimes it turns violet. So, it could be something like that … Interpretation. I definitely check my results before I become sceptical about the virtual laboratory.*

If we test the trust further…

INTERVIEWER: *… and you're still getting the same result and it's still different to the virtual lab.*

STUDENT F: *Yeah.*

INTERVIEWER: *do you think that*

STUDENT F: *virtual labs wrong*

INTERVIEWER: *Right.*

STUDENT F: *I can't keep getting it wrong.*

STUDENT G: *There's only so many times you can get it wrong.*

STUDENT F: *Or maybe like, even if you get, not just you, but someone else do it as well.*

STUDENT G: *Yeah.*

STUDENT F: *Cause then obviously it might be you, but if another person does, I think it's kinda like*

STUDENT G: *Yeah.*

STUDENT F: *… I just think sometimes if a group, if you do it, is better than just one.*

STUDENT G: *Yeah.*

STUDENT F: *So maybe I would question the labs if mine kept going. being right.*

STUDENT G: *Yeah.*

INTERVIEWER: *… you think that the virtual lab's probably right, but if you keep on, there's evidence from you doing it …*

STUDENT F: *I would question it.*

STUDENT G: *I feel like I'd have to have a lot of evidence before I said the virtual programs wrong. I think it'd take a lot for me to be like, yeah, no, I don't trust it.*

INTERVIEWER: *Right and you are trusting it because*

STUDENT F: *… Researchers go into it.*

STUDENT G: *I think you automatically presume when something's made that there's a lot of background research. It's been like peer reviewed, people have tested it. I think you just presume that it's that advance[d]. … are we over complicating?*

INTERVIEWER: *… No, no, it's fine. It's really interesting to, to, to hear you talk about it. Cause obviously you're sort of thinking about what you, what you really need to believe. You know, those are sort of questions that maybe. In the laboratory. Don't always ask yourself.*

STUDENT G: *No.*

STUDENT F: *Yeah.*

INTERVIEWER: *When you're adding these two chemicals together, how sure can you be that … chemical is what you think it is?*

STUDENT G: *Yeah. Because like the lab techs are great, but how do I know that they know that they're putting that in that bottle, that's that? … how are they a hundred percent sure that the company is sending you hydrochloric acids? It's label's hydrochloric acid. How are you a hundred percent sure that's that … it could be mixed in with something else and you would just never know.*

If you keep on getting the same result…

STUDENT D: … *It makes you more suspicious, honestly. If you repeat it again, this time probably you, you can be suspicious about the website. Maybe somehow there is a problem in the system.*

However, it is not always straightforward – Student D explains the issue like this …

STUDENT D: *It's a bit a bit complicated, if you want me to like explain to you? When we go to laboratory, [the] real one? We get some like HCL 0. 1 molar, but that one is not reliable also, it's similar to a virtual one, so probably the stuff we got it, they are not reliable or with different molar or concentration, so it's still like, the real one is not, it couldn't be reliable, we cannot try and test all of them, how they are accurate, this material we get, so, they could be similar, but sometimes … when you make when you repeat it three times, this time you can be like suspicious about yourself or that's not the virtual … You can be in between … So still, you cannot trust yourself, because … the materials they could be reliable or not.*

INTERVIEWER: *… So, you can't trust anything.*

STUDENT D: *Exactly, it's how it's science is …*

INTERVIEWER: *so you, you are equally unsure about both of them.*

STUDENT D: *If we, if based on logic, see that it can be like...something wrong in your stuff you have, or maybe in the computer in the system, so people make mistakes. It doesn't matter if it's in real or in virtual ones*

INTERVIEWER: *… how would you try and resolve that?*

STUDENT D: *Well, researching and try to use websites … Articles to find out what's what the results should be…*

INTERVIEWER: *… then you are looking for the right result?*

STUDENT D: *Yes. Well, it depends. If you're working in very high standard lab, it's, you are more definitely, you are more reliable, and being [our] College … there is some points that maybe you have to consider again …*

While some students want to trust their real experience…

STUDENT A: *… if I was more qualified and I was an actual chemist or scientist who knew what they were doing, a thousand percent, then I would trust my results, but at the stage, we're currently at … with the resources we have as well …*

INTERVIEWER: *What about if you did the virtual laboratory a number of times and that came up with the same result?*

STUDENT A: *Probably would just go for mine then, cuz I've actually done it.*

STUDENT B: *… [if] we had repeated the experiment multiple times and we got the same result, then I probably trust what we did.*

Now some of the students begin to think …

STUDENT G: *Now it's making me question like, next time I do a practical …*

INTERVIEWER: *[as your teacher] … I tell you something*

STUDENT G: *and we just go, yeah.*

STUDENT F: *That's about it. I think that's, it's all about like obviously you've got a status above us, so we kinda believe.*

STUDENT G: *Yeah. You've got like a higher authority than us, so we just, whatever you say, we go – Okay.*

STUDENT F: *I think that happens a lot … I think people above us … they could be completely wrong, but we gonna follow them because it's kind of what we've taught to follow people above us,*

STUDENT G: *it's kind of expected of you.*

Thinking now about VL…

STUDENT F: *… I think that's what it is. I think we think that these labs are being made by these companies who obviously have people who are really high up in what they do, and they've got kind of the authority and be like, this is this, and they're like, oh, that's that.*

STUDENT G: *And I'm like, now I'm thinking about it. How do you not know that? Is it just some like, 18-year-old sat in their bedroom at home programming this thing, going I think it would be 30 centimetres cubed for the titre … how do we know that it's not just someone sat in their bedroom who's never done the practical in their life, just inputting things? How do know that? I'm questioning everything now.*

INTERVIEWER: *… if you saw a video on TikTok or YouTube or whatever – would you believe?*

STUDENT F: *Well, yes. Cause you watch these like chemistry videos and how I do it and I take in the words they say,*

STUDENT G: *I think it depends on the circumstance. If like I watch a YouTube video and it, the person says they're a chemistry teacher and I've watched like a few of their videos and they seem good to me,* *then I'd believe it, but if it was just a random person on TikTok going, you add this and this together, it does this, I'd be a bit more like – absolutely? Is it? Does it? I'm not sure.*

STUDENT F: *I think it always needs proof.*

STUDENT G: *I thought you've got to like believe it a few times, for you to be secure in the knowledge.*

APPENDIX 13

T6. Risk/consequence

Students feel that there is a difference in the consequences of their actions in the real and VL, because in the VL …

STUDENT A: *… it's not gonna affect you … [if] something really, really bad happens in a lab - Oh! … you are just looking at a screen, you're like … that's not bothering me.*

STUDENT B: *… if you actually make a mistake in real life, it's gonna affect you. So, if you … forgot to put your goggles on, then something goes in your eye; and you put goggles on next time.*

STUDENT A: *… or if there's a solution that stains your skin. If it says that on virtual, then it's, oh, well it's supposed to stain my skin, but it's not cuz I'm not actually using it … or if the glassware breaks, it's not really gonna break on there … anything bad that happens in a lab is not really replicated on it.*

STUDENT B: *… [the real laboratory] engages you more, because you have to think about the … consequences of your actions … [whereas in the VL] it's not actually happening, is it? it's just on the screen.*

INTERVIEWER: *… you're starting to work in the virtual laboratory, what's the feeling?*

STUDENT E: *… so I think there's a good side about it, where everything is kind of guided and everything makes sense. You can see the equations and this quiz [and] like interactive parts of it, but there's a bad side to it as well because you're not really getting a hands-on experience, and sometimes it feels like you don't actually know what you're doing. You just putting colourful substances with colourful substances, and you don't actually know what it is. There's no consequences to get it wrong either… So, I feel like you can just retry when you have virtual laboratories. You can retry, retry even if you don't get it right. Whereas in real life, you're not gonna retry 10 times each experiment. You're not gonna have enough substance … the consequence of just wasting products … I feel like I'm more careless … it feels like I'm not really engaged …*

STUDENT G: *I think sometimes when you're sat … doing it on a computer, I think sometimes you … can just like click your way through it … I just do what it tells me to do. Whereas if you're in an actual lab, the decisions you make actually make an impact on actual chemicals, if that makes any sense. I think when you think of it as a computer, if you mix three things together wrong and it blows up, it means nothing, because it's virtual, it has no effect. You just redo it. Whereas in the actual lab, if you use all hydrochloric acid up, that's it. So, I think, your consequences mean more in a real lab, so it makes you more engaged with it.*

INTERVIEWER: *Do you feel … in the virtual laboratory … it doesn't matter what you do…?*

STUDENT B: *Well, you can't actually do whatever you want to do; it is like set rules, so you can't really make a mistake … If you do it yourself on the virtual lab and you put 15 in, it'll say that it's incorrect. So, it kinda corrects ya.*

The VL can help build skills in a 'safe' environment … make it correct.

STUDENT G: *You did it wrong a few times … it would take you the right way the next time.*

STUDENT F: *[but] …I think you don't actually learn from your mistakes … whereas in a normal lab you'd have to start all again…*

STUDENT G: *I feel like the consequence feels a lot more severe when you do it from like, I've just spent three hours doing this – I've put the wrong chemical in – I've got to start again.*

Whereas on that [the VL] you just press undo.

STUDENT C: *… [in the real laboratory] maybe doing things more carefully and accurately, like measuring something … but in the virtual laboratory, if you make a mistake, it's easier [to] take it back – so, I do enjoy that, but I prefer physical laboratory.*

STUDENT F: *… the actual lab, like if I'm measuring something out … I'll double check it, triple check it, like make sure I'm doing what I should be doing, but in the virtual lab I seem to just … kind of like cruise through it.*

STUDENT G: *… Yeah. It feels very much like you can just kind of click do it, do the steps. It feels a lot more … comfortable to do it that way, whereas when you're actually doing it yourself, you, I feel like you feel a*

STUDENT F: *pressure*

STUDENT G: *Yeah. You feel pressure. You feel pressure because obviously you … need to get it right …*

STUDENT F: *I think when you're actually, they're doing it. I think you're thinking, right, like making sure you're doing it right more; you're more conscious.*

STUDENT G: *Definitely.*

STUDENT F: *… Whereas when you're doing it online, you think, well, … if I do it wrong, the next part's just gonna, [correct it] …*

STUDENT G: *yeah. I think you take a very different approach to it … because it feels more real. You take it more, I guess,*

STUDENT F: *more seriously.*

STUDENT G: *Seriously. Yeah.*

STUDENT F: *because you've got to, in a way. [If] something goes wrong … you don't know what the outcome's gonna be.*

Students seem conscious of the consequences…

STUDENT F: *… the risk is a really big factor between the two, between the lab and the virtual. You've got so many risks that could go wrong, whereas the virtual – Exactly – Got that.*

STUDENT G: *I think it's … the consequences, it's like if I do it wrong on the laptop, you can just redo it. Whereas like doing it in real life, it's a lot harder to redo it. It takes a lot more time.*

INTERVIEWER: *And do you think that helps with your learning?*

STUDENT F: *I think the fact that you kind of got to get it right, rather than you can just redo that level … like you've got one shot … obviously you can redo … [but] some practicals take a really long time. If it goes wrong … instead of just doing the level, you've got do say's two hours practical work.*

STUDENT G: *Yeah.*

INTERVIEWER: *Do you feel like that about exams as well? The consequence of the exam …one chance.*

STUDENT F: *That is, you've got one shot. If you don't do it, then you've got to change your plan.*

STUDENT G: *You've got to then live with the consequences of that …*

INTERVIEWER: *And you feel it's the same with the lab?*

STUDENT G: *… I feel like it means a lot more to you to do it in the lab. In a way it feels a lot more rewarding because you've only got that kind of one chance when you do it right. You think, actually, I really enjoyed that outcome. You know, you tend to remember it more when you really enjoy it. Rather than like on a virtual, just saying, oh, I did it right. I could do it wrong and then do it right.*

INTERVIEWER: *… [the VLs you have used have been] very structured, but you could have a lab where effectively you could do pretty much what you wanted to ... Do you feel that that would give you more skills?*

STUDENT F: *I think you've got the chance to go wrong. Whereas with them, the ones we've been doing, you can't exactly go wrong in a way,*

STUDENT G: *if you go wrong, you just knock a couple of points off, but then you can carry on doing, say, like step two and three correctly, but if it goes down to yourself … I think you put a lot more thought into it. You've gotta think, I need that. I need to be specific. So, I think it would build a lot more skills.*

STUDENT F: *… Cause obviously there's a chance you can go wrong … So, I think it's the fact that can go wrong. So, I really need to make sure I'm doing the right things. So don't have to start all again. Which you like what you do in the actual lab.*

APPENDIX 14

Phase 3 data

This is a collection of the textual responses to the teacher survey questions organised by theme.

Hands-on: ‘physical laboratories - because they are fully in control of the process’; ‘more fun and engaging to do the science first ha[n]d’; ‘hands-on is more memorable’; ‘Hands on use of equipment re-enforces the theory that the students have learnt’; ‘I don't think virtual labs could ever replace the hands on experience of doing practicals and using the equipment first hand’; in the physical laboratory ‘they are in full control - they are the full reason whether a practical will be successful or not’; ‘Kinaesthetic learning and fine motor skills are a key element to being a good scientist’;

Real world: ‘practical work helps students learn more about the principles by putting them into practice’; ‘student learn a lot of theory through practicals first hand as it allows them to ask meaningful questions and apply the practical to real life scenarios’; ‘The handling... the idea that vessels must be placed on a flat surface, that the meniscus may not always be level or clear as a virtual lab would make it. The pitfalls that are 'unknowns' in the lab that will be removed from a programmed process’; ‘they need to know how to complete practical tasks in the ‘real world’ and not one idealized in a computer if they are to get truly competent’; the physical laboratory involves ‘team work and having to be physically involved with the equipment and be an active participant rather than an observer’; ‘Most students enjoy carrying out practicals physically. More senses are involved, such as touch and smell. Many students are stimulated by working together. They have a greater sense of achievement’; students see the physical laboratory as ‘‘real science’ rather than some kin[d] of video game’; ‘There are fewer problems in a simulation, clicking mouse buttons can be done as individuals. Physical lab experiments are more variable, present more and different challenges’.

Additional resource: ‘simulations and virtual labs can allow students to work at home at their own pace and allow more time for understanding. This can be especially true for weaker or neuro-divergent students who cannot grasp new concepts as quickly’; ‘I think they are an additional tool to help explain how to carry out a practical but learners are often not very engaged with them and may not find them very entertaining or useful’; ‘They are a good tool to complement physical practicals’; ‘virtual labs have their uses and save on resources’; ‘Very useful, esp. for the abstract ideas in science e.g. the movements within cells’; ‘I can't see why they would not be useful alongside 'real' lab work’; ‘most useful to show students how to do things before they do them’; VL ‘can also use idealised situations to illustrate a concept. Good if some equipment is not available’; ‘they are a useful addition. They help students visualise, understand and remember concepts and skills. They can make topics more interesting’.

Learning tools: VL ‘enables them to experiment with different situations quickly and safely’; ‘learners enjoy the ‘real’ experience more so they are more likely to remember the content’; ‘Practical experiences ensure students see and think about the theory in different ways which helps their understanding and learning’; ‘the physical laboratory will be better for practical skills, although a virtual lab could always be a great tool to use before a practical assessment’; ‘They learn more in a physical lab with appropriate guidance from the teacher, although virtual labs can complement this well with more continuous individual feedback possible than a single teacher with a large class’; the physical laboratory ‘engages kinaesthetic learners and uses more parts of the brain including the social areas which could lead to better embedding and long term memory’; ‘learners have completed the tasks in isolation, so sadly there was zero communication or teamwork’

APPENDIX 15

T1. Hands-on / reality

TEACHER S was asked about their experience of teaching practical science using VL and real laboratories.

INTERVIEWER: *Do you think students learn about more about the principles of scientific inquiry from virtual or physical laboratory?*

TEACHER S: *Definitely physical, 100%; because they're also developing so many skills that you need for doing the practical, not just, you know, the fiddly things that you're doing with the equipment, but also the social skills you need to, to be able to use equipment. Often it takes two or three people … working simultaneously. I just don't think it, it would work as well, and it won't prepare you for the different textures of the … things you're dissecting for, the different way you're gonna feel when you're dissecting something like that. I mean, a lot of my students faint when they do it. So … there's emotions attached to it and that helps with learning … and forming those long-term memories.* ***INTERVIEWER:*** *… [Do] they see the virtual laboratory as like the real laboratory, like a mirror of the*

real laboratory? ….

TEACHER S: *No, I think …. they see things in real life, and they see that … it is a mirror of what we do in the lab. I've always pitched it like that, and I think they do see it that way … we did [a] polymerase chain reaction … set it up and then we did a virtual lab on it, and they were like, oh yeah, like [before], like they can see that it is representing what we do in the lab, and I think they have no trouble with that concept as far as I'm aware.*

INTERVIEWER: *… what about the real lab to how much … do they believe the results they're getting from that?*

TEACHER S: *Well, they know sometimes some of my … mock-ups, right. I just tell them the truth. I'm like, this is a model. This is not real life. I'm not using the actual enzyme. Just pretending, but I think because they see how the results are different each time and how, you know, the results are never quite what you expect. They can see that they're collecting … real data and I think they appreciate that because then we can have really interesting discussions about like, why was that data not perfect … what variables can we not control in biology and, and … why do we have to do a mean, because there's so many different … things that could be affecting the results today. And I think, they see that biology is real and tangible through that, through the sometimes untrustworthiness of the results, you can get a real sense of how to use it, but like, that's why I really find wildly exciting because sometimes you just get unexpected results. And then you have to have fun trying to explain it, but yeah, I think because they're doing it themselves, they know what equipment they're using, and they have autonomy over the results they're getting. I think they feel like they can trust the results because they're the ones who created their own space in the first place.*

TEACHER T: *… I'm going to talk about titration … So, the meniscus, whether it's 0. 05, 0. 00, I think you could get that kind of skill and knowing, … what are the numbers I need to record here, I think you could get that from [either laboratory]. I think the difficulties of judging an end point would be far better done … with a real colour change, because there's no idea how they do colour change shades on in the virtual world … what is one person's burnt orange is another person's completely red. So, I think they would get some practical element, useful practical skills … but some of the more qualitative ideas about colour changes would be better in reality.*

… if you're working in a group on a virtual lab or on physical lab, I think it would be physical without a doubt [would be better], … if your team is depending on something happening in front of them … [also] the skills around that … splitting of duties, washing up, cleaning up, getting things out is, has to be done physically …

[Students on] health related courses … like being around people, they like talking to people, they like interacting with them; and the physical, practical work allows all of that … it instils … camaraderie and I think the students, that I have, going into health professions … enjoy that and enjoy working with each other ...

APPENDIX 16

T2. Doing it myself / Control

TEACHER S: *… [In the VL everything] works fine and there's no waiting, there's no … having to problem solve particularly, you just … go work through the steps. Whereas, in a real lab, something's gone wrong, something's not working - they have to figure it out. They have to figure out which equipment piece needs replacing or fixing or cleaning and … sometimes it doesn't work. So, they have to go back and think, right, okay, this time I'm gonna try a slightly different concentration. I think that kind of … on the spot problem solving and quick thinking and teamwork and communication, it all comes together into one cohesive learning experience. That's really valuable.*

While in the real laboratory – *They can see that they're collecting … real data and I think they appreciate that because then we can have really interesting discussions about like, why was that data not perfect … what variables can we not control in biology and, and … why do we have to do a mean, because there's so many different … things that could be affecting the results today. And I think, they see that biology is real and tangible through that, through the sometimes untrustworthiness of the results, you can get a real sense of how to use it, but like, that's why I really find wildly exciting because sometimes you just get unexpected results. And then you have to have fun trying to explain it, but yeah, I think because they're doing it themselves, they know what equipment they're using, and they have autonomy over the results they're getting. I think they feel like they can trust the results because they're the ones who created their own space in the first place.*

… *I think there's just more inputs … different kinds of stimuli hitting you at once ... Instead of just visual information and auditory information, you are also having to sort of feel things, having to think about things, having to talk as well as do the practical. So, it's multitasking skills as well; all of which are gonna be useful in later life – it's not just developing skills in science. They're developing skills for life and they're gonna have to work with … problems and people their whole lives.*

Students feel that their own results are more authentic, for example ***– TEACHER S:*** *… sometimes when I give them … data from an exam question, they're like, oh, but we didn't quite get that in our results … they're always like referring back to their own results and I think they sometimes trust those more because they saw it happen with their own eyes instead of just like, numbers on a piece of paper. And I'm like … this is more like what you're supposed to get and they're like, yeah, but we got this, and I think … they tend to trust their own results sometimes a bit more.*

APPENDIX 17

T3. Method / skills

The teachers were asked about what was valuable in practical science for their students.

For ***TEACHER S:*** *… doing the [real] practical, not just … the fiddly things that you're doing with the equipment, but also the social skills you need to, to be able to use equipment. Often it takes two or three people, it's working simultaneously. Someone's gotta start the stopwatch while you, you know, add the liver to the hydrogen peroxide … encompasses so many more different social elements to it, as well as fine tuning the fine motor skills you need for a lot of different practicals, like some of the dissection practicals – there's no way you'd be able to learn that online and then someone says, right, okay, go and dissect a heart using your knowledge from all that you've learned online. I just don't think it, it would work as well, and it won't prepare you for the different textures of the, you know, the things you're dissecting for, the different way you're gonna feel when you're dissecting something like that.*

INTERVIEWER: *what about for students who, who are too anxious to do a dissection?*

TEACHER S: *… [They could] do something virtually. I've never thought of that before. That could be a really good way of filling that gap, I suppose. Cuz there are questions on dissections in the exam, but we do offer an alternative plants dissection … which is not quite the same, but it uses a lot of the same skills … even if they don't do their heart or fish dissections …*

I think being in the [real] lab teaches them far more practical skills … there's so many different elements to your practical, it's not just the theory of doing it, it's not just the step-by-step plan, it's … the social aspects, where you need to be, what you need to do at each moment, and how that actually all works together … in one experiment we have to hold … several things underwater while someone else is starting stop watch, someone else is getting the next potato sample. So that's something you can't really prepare for virtually. So, I think a lot of the practical skills you learn physically are, so I say it, they're far more useful for the future … if you had to do that practical again … you'd be far more likely to do better, having done it once before; than having learned about it virtually and just looked at the theory of it. You sort of made that muscle memory almost.

… *we do a lot of microscopy skills, and a lot of biology jobs involve a lot of microscopy, so that's something that's quite transferable.*

… I've just remembered PAG 10 is … virtual, I don't think it's a virtual lab, but … manipulate molecules on the computer program and like measure things … on the DNA molecule. So, some of the things we do are using … computer modelling, so that is gonna prepare them for … industry in the future ... I think all of our practicals do prepare for no … matter what industry [you] go into …

… *[the students] manipulate a molecule using a program or an online resource… [a] DNA molecule and they sort of wiggle it around and measure things.*

INTERVIEWER: *Do you think students gain skills from the VL?*

TEACHER S: *… communication if they're reading and having to interpret information, and if there's follow up questions in the virtual lab … [they are] developing their understanding and reasoning. But I think there's far more higher order skills that are developed through doing a real practical. … evaluation, you can do virtually that …they can evaluate improvements for a practical … in theory as well as in practice. So that's a high order skill that they can do ... Teamwork's definitely one that's developed better in a real laboratory rather than a virtual lab … you are usually doing that alone …*

perseverance, that's definitely needed in some of my … biology practicals; but with the virtual lab, everything works instantly. … there's no, you know, having to problem solve, particularly … go work through the steps; whereas in a real lab, something's gone wrong, something's not working they have to figure it out. They have to figure out which equipment piece needs replacing or fixing or cleaning and then yeah, sometimes it doesn't work. So, they have to go back and think, right, okay, this time I'm gonna try a slightly different concentration.

I think that kind of you know, on the spot, problem solving and quick thinking and, and teamwork and communication, it all comes together into one cohesive learning experience. That's really valuable.

***…** Different kinds of stimuli hitting you at once … Instead of just visual information and auditory information, you are also having to sort of feel things, having to think about things, having to talk as well as do the practical. So, it's multitasking skills as well … they're developing skills for life.*

***INTERVIEWER:** … do you have an overall impression of how students learn using … virtual laboratories …?*

***TEACHER S:** … they're learning visually. They have auditory sometimes as well. It can be kinaesthetic, like, you know, in some of them you have to move with your mouse things and put it in that tube, there is some evaluating as well. So, they're developing their higher order skills and there could be a little bit of communication kind of because they are taking in information and reinterpreting it into some questions and answers … they're also learning alone a lot of the time, so it's independent learning, which is [a] good skill for university.*

***TEACHER T: …** I'm going to talk about titration … So, the meniscus, whether it's 0. 05, 0. 00, I think you could get that kind of skill and knowing; right – what are the numbers I need to record here. I think you could get that from [VL]. I think the difficulties of judging an end point, would be far better… with a real colour change … what is one person's burnt orange is another person's completely red. So, I think they would get some … useful practical skills like measurement easily from online measurement in numbers … but some of the more qualitative ideas … would be better in reality.*

… in the practical world … the skills … include the … splitting of duties, washing up, cleaning up, getting things out it has to be done physically… I certainly think teamwork … would be better … in the laboratory because at the end of the day, like we say, someone has to clean it away.

Someone has to get all the equipment ready and such, yes, technicians will help with that, but the perpetrators of the practical will have, will have to be responsible for some of it. So, I think teamwork certainly comes into it and, you know, cleaning up at the end and getting things ready is part of teamwork.

[Students on] health related courses … like being around people, they like talking to people, they like interacting with them; and the physical, practical work allows all of that … it instils … camaraderie and I think the students, that I have, going into health professions … enjoy that and enjoy working with each other ...

… in terms of higher-level skills? … abstract concepts that might come into it; I think any would be fine for it. I don't think that a practical laboratory would necessarily benefit you persistently, consistently for those high-level skills of evaluating – why an experiment worked well, why it didn't, why you were getting a low yield, a higher yield.

… abstraction – I think it is that; at the minute we can use virtual laboratories, we can see things that we couldn't see before… we are moving on with that kind of abstract ideas. Development and seeing them in action … but … I don't think … there's a benefit of one over the other.

APPENDIX 18

T5. Trust / Truth

INTERVIEWER: *… to what extent do students regard the experiments conducted as trustworthy?*

TEACHER S: *… in the virtual lab? … I think … young people especially have a tendency to just believe things they see on the internet … I'm never really sure in some of these labs, the virtual labs, if the results are finite and set, pre-set, or if they use like a random number generator or something. It'd be probably more realistic if they use the random number generator because sometimes the numbers we get are just … within like set limits, but that would be quite useful cuz it kind of mirrors more like what, what you're gonna get in real life and that's why you do a mean, but I think sometimes they just use set numbers, you know, like you will get 2%, 4%, 6%, and it doesn't always work that way. So, I think the students probably regard the … virtual labs as kind of like a best-case scenario result – Not very realistic, but still fairly reliable, if that makes sense.*

INTERVIEWER: *… the real lab to how much do they, do they believe the results they're getting from that?*

TEACHER S: *… Well, they know sometimes some of my … mock-ups ... I just tell them the truth. I'm like, this is a model, this is not real life – I'm not using the actual enzyme – Just pretending. But I think because they see how the results are different each time and how … the results are never quite what you expect. They can see that they're collecting … real data. And I think they appreciate that because then we can have really interesting discussions about like, why was that data not perfect … what variables can we not control in biology … why do we have to do a mean, because there's so many different … things that could be affecting the results today … they see that biology is real and tangible … through the … sometimes untrustworthiness of the results, you can get a real sense of … why I really find wildly exciting because sometimes you just get unexpected results and then you have to have fun trying to explain it.*

… *I think because they're doing it themselves, they know … what equipment they're using, and they have autonomy over the results they're getting. I think … they feel like they can trust the results because they're the ones who created their own space in the first place.*

INTERVIEWER: *So, you think that if there was a conflict between the two, they would trust their results from the real laboratory over those from a virtual laboratory?*

TEACHER S: *Yes. And sometimes when I give them … data from an exam question, they're like, oh, but we didn't quite get that in our results … they're always like referring back to their own results and I think they sometimes trust those more because they saw it happen with their own eyes instead of just like, numbers on a piece of paper. And I'm like … this is more like what you're supposed to get and they're like, yeah, but we got this, and I think … they tend to trust their own results sometimes a bit more.*

INTERVIEWER: *… even though you tell them, okay, this is what you should have got*

TEACHER S: *there's always still the pushback. Yeah, but we got this … I suppose that sparks debate, but I think they do get that in science … this is the set data and what we get will always slightly differ, cause that's just the way it is.*

INTERVIEWER: *… how much confidence do you have in the educational value of virtual laboratories?*

TEACHER S: *I'd say, I'd say quite a lot, because most of them are made by … sort of quite reputable universities or companies. … I trust … that they have done their research and they've got everything right, as you always sort of check through them though, is that not being trustworthy then?*

Because I always do check through them, so maybe I don't have a hundred percent, but … 99% sure that, I'm confident in what, that information is correct, but I do like to go through and check them just to make sure they're right for OCR … I'd say … pretty confident.

INTERVIEWER: *… that shows trustworthiness in the sense that you've gone through a process which assures you …*

TEACHER S: *… quality assurance test … I'm confident that [it] explains things correctly, but at the same time, I do always just double check … I've not really found any that are wrong …*

INTERVIEWER: *… if there was a big conflict between [the real laboratory and the VL]*

TEACHER S: *… a huge, like ridiculous conflict? … we have had that actually before … we did have an experiment that just went totally wrong, and we got the complete opposite relationships and what we shouldn't be seeing. And I can't help thinking that either … the technician or some something went wrong somewhere in the dilution, and either were labelled maybe, and that could have been why it went wrong … at the end of the experiment I was like, well, that didn't quite work how we planned … what could that have been? Why do you think that happened? Again, promoting good discussion. That's something you don't get in a virtual lab … just trying to figure out what went wrong and improve the next time … they learn that they always have to evaluate, think back, and then repeat the experiments to try and get the correct results in the future, but … in science you sometimes you find something new, don't you? … if something's not following the pattern, you might repeat it and see if it happens again, and then think, okay, now I discover[ed] something new.*

INTERVIEWER: *… the extent to which students regard the results of the experiments, conducted in either environment as trustworthy.*

TEACHER T: *… in terms of them being real results, I think they would undoubtedly pick the, the in-class practical work ... if I said to them, you're gonna do two practicals, you're gonna do one in class, you're gonna do one via a computer, which do you think … would give you the closest results to the true value? They probably say the computer, but if I asked them why, they would say … because it's a computer … it's gonna tell me the right answer. … but if I said … which ones, do you think people are, if they do the experiment themselves … more likely to get? … not necessarily the accurate ones nearest the value – what are they more likely to get? I think they would pick the … in-class practical work.*

INTERVIEWER: *Why do you think they would trust the computer?*

TEACHER T: *… because I think they would imagine, well, [(teacher's name) is] gonna have doctored it. He's not gonna give us a program that would just give us nonsense results, irrelevant results. I think they would believe that the results they get … from the computer would've been in some way doctored to be closer to the [right value], I think that anyway.*

INTERVIEWER: *And you think that's because they would trust you?*

TEACHER T: *I think that's because they would trust me, to not allow them … to go down on a wild goose chase. … go off on a tangent and get ridiculous results. I think they would think, well – know, the lesson will have been sculpted in some way to not allow that and the practical work would reflect that … that's my perception … of my type of student.*

INTERVIEWER: *… do you think that's the same with the physical practical laboratory …*

TEACHER T: *no, no, because my experience of doing the physical practical is you will get some students, some groups who get ridiculous results. …. It's a bit of fun, when that happens, but … they would at least trust them and say, well, something went wrong, something actually went wrong, we did something wrong, and we can investigate what that was, of course … they do trust them in as much as, well, they were the real results we got, even if they were completely different to everyone else's in the class. Whereas, if that was in a virtual environment, I think they would suspect well, that was probably done on purpose to give that outlier to provoke some debate rather than it just happening because they had done something wrong.*

APPENDIX 19

Image analysis

Introduction

The RSC titration screen experiments are one form of VL. These provide a fairly structured set of activities based around particular scenarios. All my A level chemistry students carried out, the Level 1 titration activity, as well as the corresponding real titration experiment. They were familiar with titrations before completing these activities as titration is routinely taught at GCSE level.

In this section I have tried to analyse something of the experience of the students when working through the VL. This could be done through a number of lenses, but I have chosen to use the Gestalt principles (Wertheimer, 1923; and discussed in Chapter 3), as my main guide. This provides a framework of ideas around the concept of 'wholeness' and how an image, or experience, is more than the sum of its parts. Figure 37 shows a typical scene from VL, it can be seen that bottles are represented simply by a continuous line which thickens to indicate the cap. The impression of a liquid is given by shading within vessels.

Stahre Wästberg et al. (2019) have carried out an in-depth comparison between the design of different VLs and they propose that the designer should: 'Guide the design work with a clear understanding of purpose and context; select appropriate technology to ensure efficient design and media usage; select level of realism considering purpose and end users; and provide learning guides before and after the virtual lab session'. Detailed analysis is beyond the scope of this work, but an area of some interest.

The overall effect

Gestalt theory tells us that we should consider the *whole*, so any analysis should be general, rather than detailed, giving the picture as one entity. I will attempt to analyse the VL using the Gestalt principles, given in Chapter 3. I am starting with my overall impression which, I feel, is related most strongly related to continuity:

Continuity

The whole experiment is presented as a narrative story, in which the student becomes a participant. The material is presented as a series of pages, with activities on each. A guide, in the form of Dr Patel, is present on every page, to provide help, on the journey. There is a constant layout and colour scheme for the pages, giving the impression of a continuing event. Progress though these pages is shown by a series of dots at the bottom of each page, which are progressively turned orange as we move through the pages, indicating continuing progress. This means working through the pages feels more like a progression, than a series of disconnected activities. There is a lab book which provides a continuing record of each activity and activities are related back to the overarching story. In Figure 38 the retort stand is incomplete at the left side of the picture, Gestalt continuity and closure help us to "see" the remaining parts, beyond the edge of the picture.

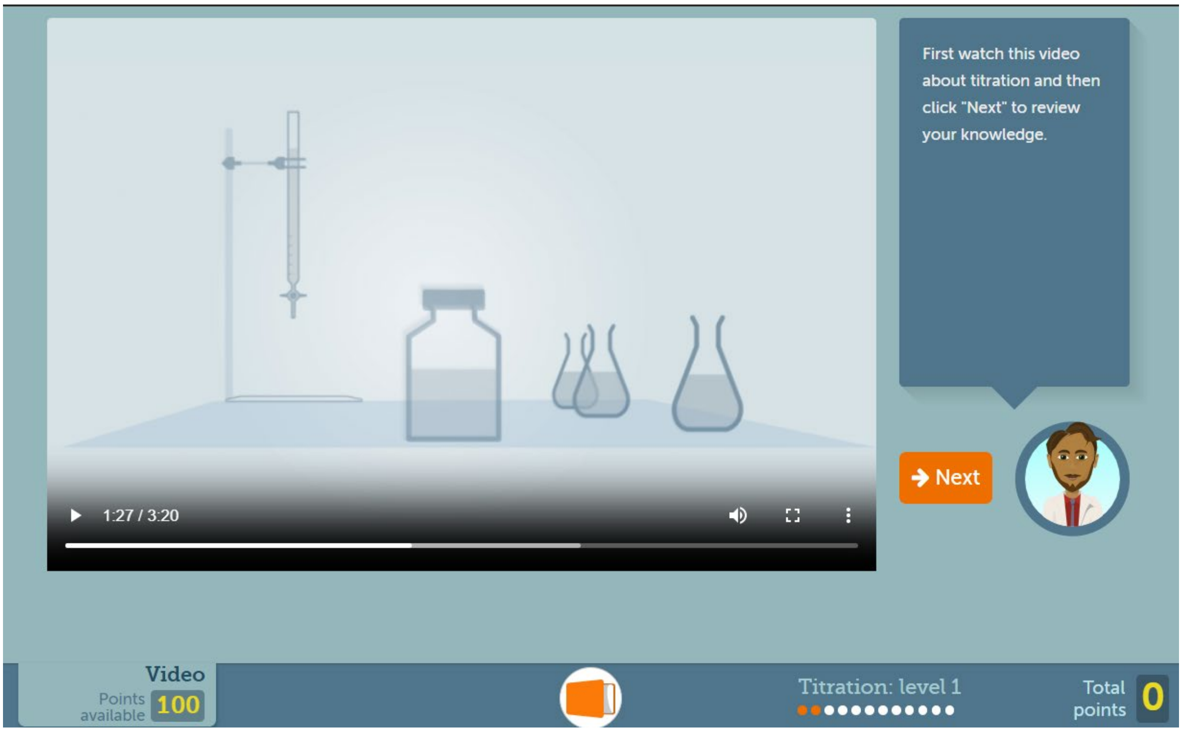

Figure 37 showing a still from the introductory video part of the level 1 Titration RSC Screen Experiment

(https://virtual.edu.rsc.org/titration/experiment/2/5 Accessed 12/4/23)

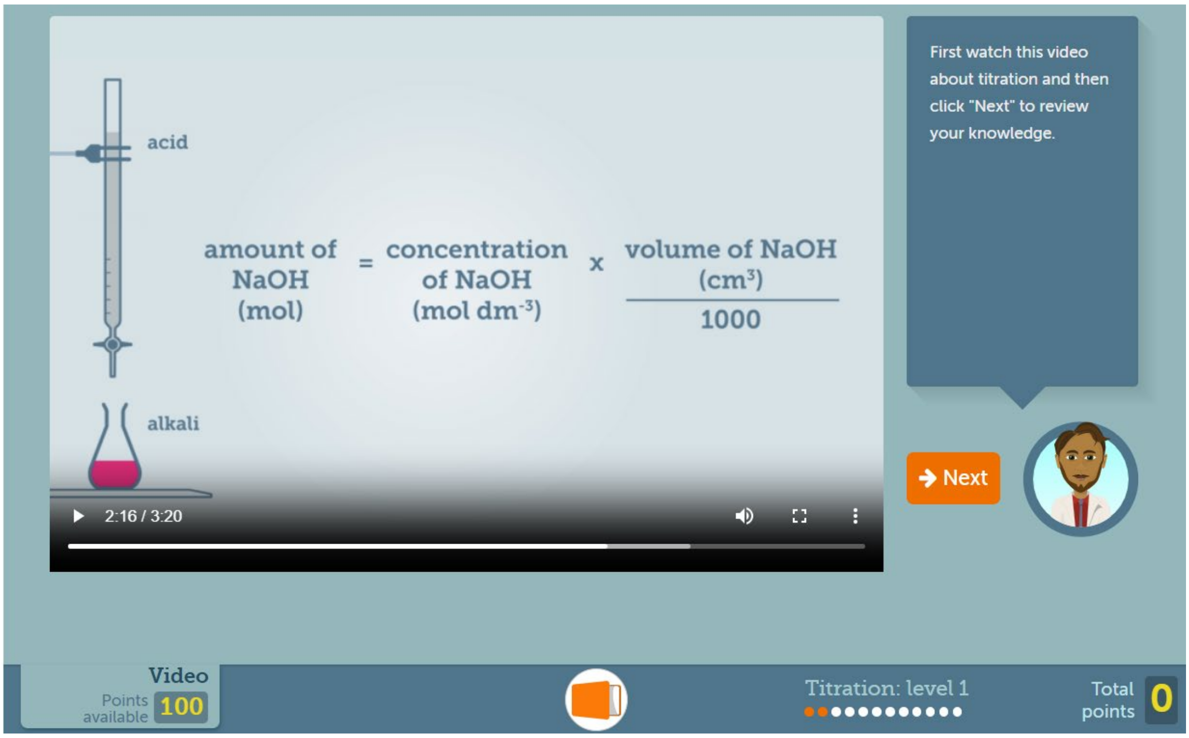

Figure 38 showing a second still from the introduction video from the level 1 Titration RSC Screen Experiment

([https://virtual.edu.rsc.org/titration/experiment/2/5 Accessed 12/4/23](https://virtual.edu.rsc.org/titration/experiment/2/5))

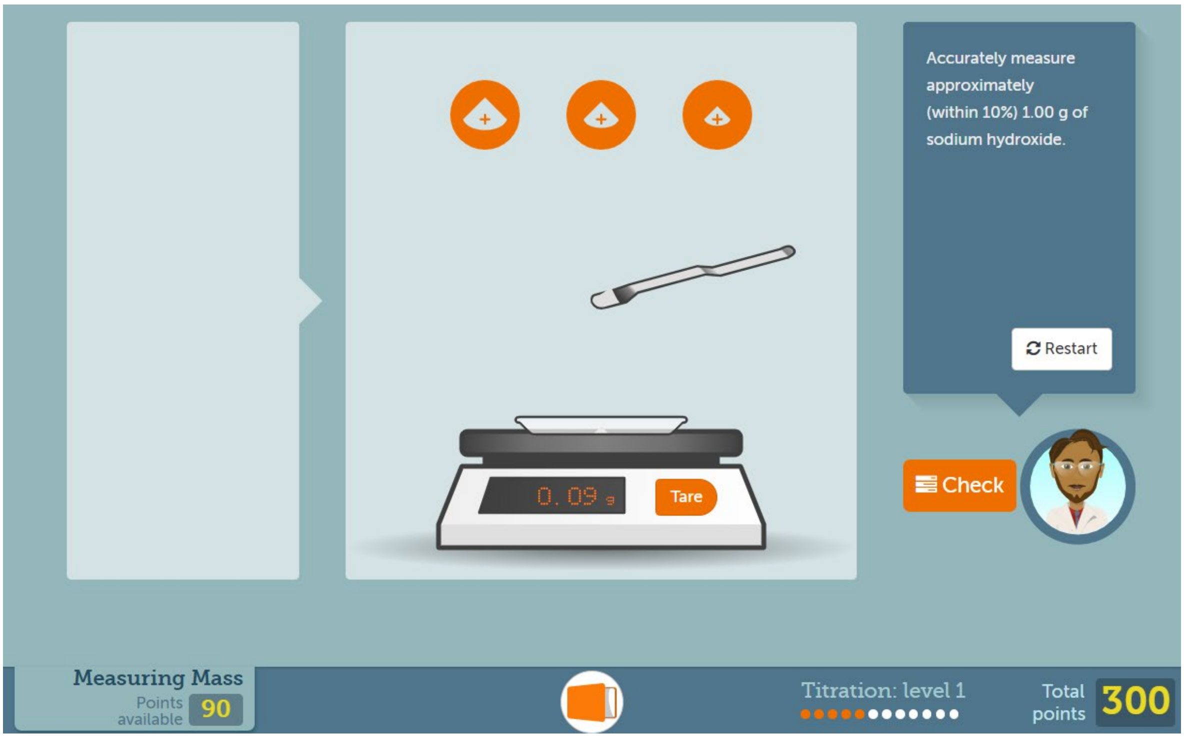

Figure 39 showing the weighing of a solid from the level 1 Titration RSC Screen Experiment

(https://virtual.edu.rsc.org/titration/experiment/2/5 Accessed 12/4/23)

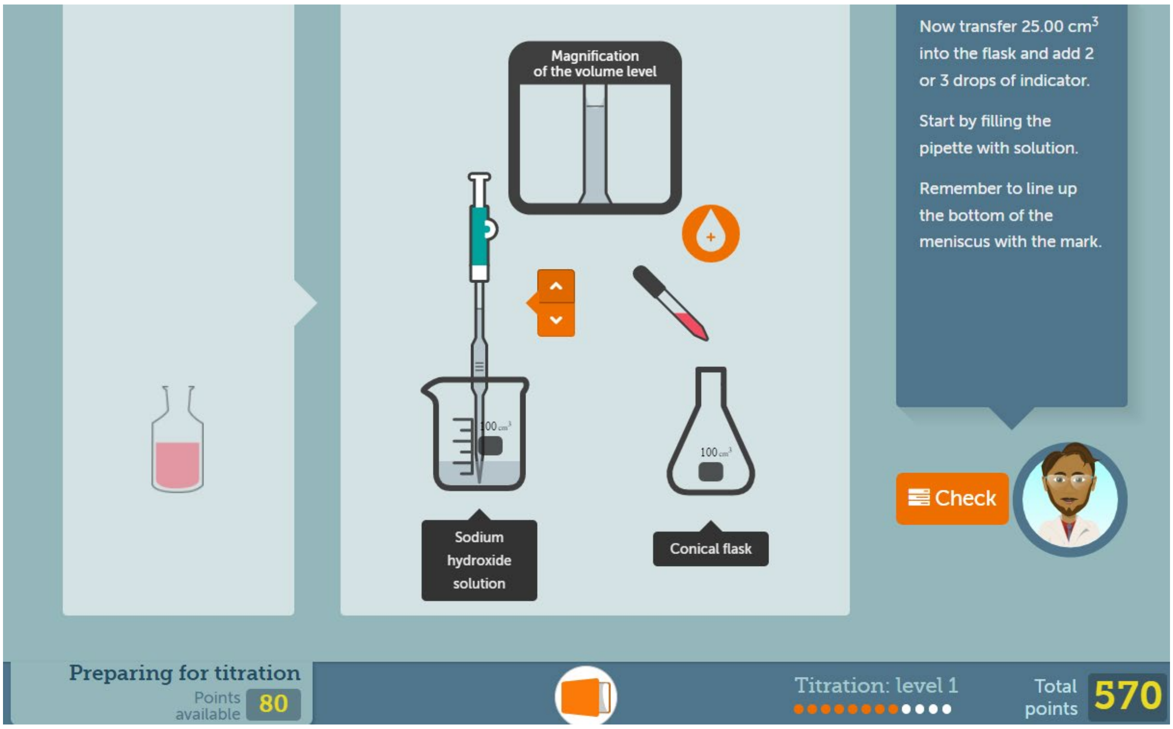

Figure 40 showing the process of filling the pipette from the level 1 Titration RSC Screen Experiment

(https://virtual.edu.rsc.org/titration/experiment/2/5 Accessed 12/4/23)

Figure 41 showing a titration experiment related to a map and results table, from the level 1 Titration RSC Screen Experiment

(https://virtual.edu.rsc.org/titration/experiment/2/5 Accessed 12/4/23)

Similarity

A suggested above the similarity of layout and colour scheme for each page, helps them appear connected; as does the presence of Dr Patel. There is also a similarity of colours, orange to represent the current activity on a page, answers in green correct and red wrong. Colour is also used to link parts of the screen. For example, in Figure 41, the orange colour links the site on the map (B), the table column and cell, with the help panel below the flask.

Similar objects are displayed in the same way, for example, stylised glassware with a single dark outline, liquids as grey. There is a change when a real flask is substituted to show a real colour change. To me this does seem a discontinuity, where it takes a moment to recognise the two representations of the flask are of the same thing. However, there is enough similarity for me, and I think others, to recognise it as the same thing.

Proximity

Figure 41, shows how the proximity of items on a common page connects ideas, here three things are connected: the titration experiment apparatus; a table showing the results of the titration and a map identifying where a sample has been taken from. By placing these on the same page, their proximity, relates them – we see the sample comes from a certain site, is analysed in a certain way and give results which are connected.

Common fate

During the video section (see Figure 37 and Figure 38) bottles and flasks are moved, the darker area in the lower parts of these are then interpreted as liquids contained within them as they move together: they have a common fate. This is also seen in Figure 39 where a solid is weighed on a balance. Although the movement of the actual solid is not shown explicitly, the spatula, which would carry the solid, moves to the weighing boat. Thus, by the idea of common fate, the solid appears to be transferred to the weighing boat on the balance.

Figure-ground

The figure-ground distinction is achieved in several ways, see Figure 37 to Figure 40. The overall background is a pale blue with featured panels apparently superimposed. One to the left contains a small image of Dr Patel and a further panel for his comments, indicated by a rectangle with a small triangle pointing from it towards Dr Patel. This is reminiscent of the conventional 'speech bubble', widely used in cartoons etc. A second foreground panel is a strip across the bottom, this contains the functional items, the activity title, points available for this activity, points total, the progress indicator and a link to the laboratory book. The main activity panel is a very light blue rectangle situated to the upper left. Within this panel, depth is indicated by the use of darker lines to indicate closer (and more significant) items. Perspective is achieved by the use of trapeziums (see bench shape in Figure 37 and retort stand base in Figure 41); also, by apparent object size (see flasks reducing into the distance in Figure 37). A further device is the use of bold lines to indicate closer objects, with more distant objects in thinner, paler lines (compare the bottle (foreground) and burette (background) in Figure 37).

Closure

In Figure 38 the retort stand is incomplete at the left side of the picture, Gestalt continuity and closure help us to see the remaining parts, beyond the edge of the picture. Closure is also invited in Figure 40, where the bottle in the left panel is drawn with a gap in the line defining its shape, which is completed in my mind as an entire vessel.

Symmetry

Although, symmetry is not a strong feature in the RSC activity, there are many approximately symmetrical objects just as there are in the real laboratory.

Summary

This section shows briefly that the RSC activity can be viewed through the lens of Gestalt, which helps to create an overall experience for the learners. The activity is analysed to show that these principles are applicable and how each is important in the overall experience for the students.