The Effects of Convolution Reverberation on the Emotional Characteristics of Musical Instrument Sounds

Abstract

Previous work has shown that the emotional characteristics of musical instrument sounds are significantly changed with parametric reverberation (Anonymous 2022). But, do the parametric reverberation results also apply to real concert hall reverberation? This paper considers the effects of reverberation time on the emotional characteristics of instrument sounds with convolution reverberation. We compared eight musical instruments and ten emotional characteristics over five hall impulse responses ranging from the 1-second Royal National Theatre to the 5-second King's College Chapel. The results showed that convolution reverberation had more pronounced effects on emotional characteristics compared to parametric reverberation. This makes sense since convolution reverberation is often regarded as warmer, more natural, and smoother than parametric reverberation, which is often regarded as blander by comparison. Halls with shorter reverberation times emphasized the emotional characteristics Angry and Comic, while medium reverberation times emphasized the characteristics of Happy, Heroic, and Shy, and longer reverberation times emphasized the characteristics of Calm, Mysterious, Romantic, Sad, and Scary. While the results were more pronounced for convolution reverberation compared to parametric reverberation, there was also a strikingly strong agreement in their results, and the correlation coefficient between them was 0.74 over all emotional characteristics. This strong correlation indicates that reverberation time has a remarkably consistent effect on the emotional characteristics regardless of whether using convolution or parametric reverberation — a reflection of their deep underlying functional similarities despite their fundamentally different

implementations.

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When someone thinks of a piece of music, they often think of its melody. They might also consider other striking features related to tempo, dynamics, pitch range, mode, or harmony. The instrument playing the melody, and the spaciousness of the place where it is played also shape the emotional characteristics of the music (Tajadura-Jiménez et al. 2010; Anonymous 2022), and are the topic of this paper.

It is obvious even to a non-musician that an instrument such as a violin can express a very wide range of emotional characteristics depending on the musical context. But, at the same time, each instrument has its distinct sound color that may tend to bring out particular emotional characteristics (Scherer and Oshinsky 1977; Eerola et al. 2012; Wu et al. 2013, 2014c, a, b; Chau et al. 2014, 2015b; Chau and Horner 2015, 2016; Williams 2016). Further, our previous work has shown that the emotional characteristics of instruments are significantly changed with parametric reverberation (Anonymous 2022) and that these changes are remarkably instrument-independent (Anonymous 2022). Of course, the musical context (e.g., the melody), has its emotional characteristics that are colored by both the instrument and reverberation.

Parametric reverberation was a natural starting place for our initial investigations, since the parameters, namely reverberation length (i.e., a parameter within the reverb generator that roughly corresponds to the reverberation time) and amount (i.e., wet/dry ratio), were easy to control and manipulate. But, do the results from parametric reverberation apply to real concert hall reverberation as well? This is a critical next step since convolution reverberation is very popular and even more frequently used than parametric reverberation, and it is a better indicator of how instruments sound in real concert hall environments (Valimaki et al. 2012). Convolution reverberation is a bit more complex in the sense that it depends on particular impulse responses measured in real halls at discrete points. In other words, with convolution reverberation, you are working with impulse responses at a few discrete points in the hall, while with parametric reverberation you have a continuum of parameter values for the reverberation amount and reverberation time.

In any case, it would be useful to have the results for both convolution and parametric reverberation, since they are both widely used for musical instruments, and yet they are fundamentally different. Convolution reverberation is often regarded as smoother, warmer, and more natural than parametric reverberation, so the emotional characteristics could be basically similar, further enhanced, or completely different.

In this study, we seek to understand how the emotional characteristics of musical instruments vary with reverberation time in convolution reverberation. In our previous study on parametric reverberation, reverberation time and amount had strongly significant effects on the emotional characteristics of Romantic and Mysterious, and medium effects on Sad, Scary, and Heroic. Anechoic tones were judged most Comic. We are particularly interested to compare and contrast these results to those for convolution reverberation.

The work will give audio engineers and musicians an interesting perspective on reverberation since many recordings are done in studios where the type and quantity of artificial reverberation added is decided by recording engineers and performers. The work also has applications in music designed for virtual environments, computer games, film soundtracks, and karaoke systems by adjusting reverberation to emphasize desired emotional characteristics.

Previous Work on Music Emotion and Artificial

Reverberation

Researchers have considered various relationships between timbre (sound color) and music emotion (Hevner 1936; Peretz et al. 1998; Tzanetakis and Cook 2002; Ellermeier et al. 2004; Aucouturier et al. 2005; Bigand et al. 2005; Yang et al. 2008; Zentner et al. 2008; Hailstone et al. 2009; Filipic et al. 2010; Krumhansl 2010; Eerola and Vuoskoski 2011; Vuoskoski and Eerola 2011; Asutay et al. 2012; Baume 2013; Liebetrau et al. 2013). In particular, they have found that different instruments have different timbral and emotional characteristics (Scherer and Oshinsky 1977; Eerola et al. 2012; Wu et al. 2013, 2014c, a, b; Chau et al. 2014, 2015b). By changing the pitch, dynamics, and other aspects of the performance, the timbre and emotional characteristics also change (Balkwill and Thompson 1999; Skowronek et al. 2007; Ekman and Kajastila 2009; Hu et al. 2009; Liebetrau et al. 2012; Plewa and Kostek 2012; Lahdelma and Eerola 2014; Chau and Horner 2015; Williams 2016; Chau et al. 2016; Chau and Horner 2016; Chau et al. 2017; Chan et al. 2018, 2019; Hong et al. 2018). These timbral and emotional characteristics are further modified by the performance environment - by the amount and length of reverberation in the space (Cremer et al. 1982; Rumsey 2016), which smears the temporal and spectral envelopes and changes the emotional character of the sound (Västfjäll et al. 2002; Tajadura-Jiménez et al. 2010; Williams 2016). The same idea holds when artificial reverberation is added as a post-process. To put the current investigation into context, background work in artificial reverberation is reviewed in the following subsection.

Artificial Reverberation

Various models have been suggested for reverberation using different methods to simulate the build-up and decay of reflections in a hall as the sound is absorbed by surfaces of objects in the space. They include simple reverberation algorithms using several feedback delays to create a decaying series of echoes, such as Schroeder reverb (Schroeder 1962). More sophisticated algorithms simulate the time and frequency response of a hall, using its dimensions, absorption, and other properties (Schroeder 1970; Moorer 1979; Jot and Chaigne 1991; Gardner 1992a, b). These approaches are often regarded as parametric artificial reverberation methods, or simply *parametric reverberation* (Valimaki et al. 2012). There are also *impulse reverberation* or *convolutional reverberation* models that convolve the impulse response of the actual space being modeled, such as concert halls, with the audio signal to be reverberated (Reilly and McGrath 1995; Farina 2000). Generally,

These models use different parameters, but in all of them, it is possible to characterize the reverberation by characteristics such as reverberation time and early decay time. Reverberation time (RT_{60}) is one of the most important characteristics of reverberation, and measures the time reverberation takes to decay by 60dB SPL from an initial impulse (Sabine and Egan 1994). Jordan (Jordan 1970) suggested an alternative measurement called Early Decay Time (EDT), which is defined as either: (1) 6 times the time interval that it takes for an impulse response to decay from 0dB to -10dB, or (2) by the straight line that best fits an impulse response as it decays from 0dB to -10dB.

Some previous research has considered the subjective evaluation of reverberation. In a preliminary study, Kaczmarek et al. (Kaczmarek et al. 1999) subjectively evaluated reverberation amount using individual anechoic instrument tones. They ran two experiments. In the first, listeners rated tones with 0%, 30%, and 60% reverb based on sound characteristics such as Bright, Dark, Natural, Rumbling, and Sharp. However, the reported results were brief and inconclusive. In their second experiment, they used A-B-A comparisons of various levels of reverb in terms of naturalness, which decreased with more reverberation.

Though various research has shown the effects of reverberation and room geometry on clarity, spaciousness, and other perceptual aspects of speech and music (e.g., Cremer and Müller (Cremer et al. 1982)), only a few studies have considered the emotional effect of reverberation. Västfjäll et al. (Västfjäll et al. 2002) studied how reverberation time influences emotion in musical excerpts. They used a dimensional model to measure the effects on Valence and Arousal. They found that long reverberation times were perceived as the most unpleasant. More recently, Tajadura-Jiménez et al. (Tajadura-Jiménez et al. 2010) studied the correlation between emotion and room size for four natural and four artificial sounds. They also used a dimensional model with measurements for Valence, Arousal, and perceived Safeness. Their results suggested that smaller rooms were considered more pleasant, calmer, and safer than big rooms, although these differences seemed to disappear for threatening sound sources.

Our Studies on the Emotional Characteristics of Parametric Reverberation

We performed several studies on the emotional characteristics of artificial reverberation (Anonymous 2022). Particularly, two studies were on parametric reverberation.(Anonymous 2022). In the first study, we wanted to determine how the emotional characteristics of instruments vary with reverberation length and amount (Anonymous 2022). In other words, roughly how the emotional characteristics vary with hall size and listener position relative to the front or back of the hall. We found that reverberation length and the amount had strongly significant effects on the emotional characteristics of Romantic and Mysterious, and a medium effect on Sad, Scary, and Heroic. Reverb had a mild effect on Happy, and relatively little effect on Shy. Interestingly, for Comic, reverberation length and the amount had the opposite effect; that is, anechoic tones were judged as most Comic.

Another interesting aspect of our parametric reverberation results was that they demonstrated how the categorical emotional model can potentially give more emotional nuance and detail than a 2D model with only Valence and Arousal. Our data showed very different results for the high-Valence emotional categories Happy, Heroic, Comic, and Romantic. The results of Västfjäll (Västfjäll et al. 2002) and Tajadura-Jiménez (Tajadura-Jiménez et al. 2010) suggested that all four of these high-Valence emotional characteristics would be stronger in smaller rooms. But in our results, only Happy and Comic were stronger for small halls, while Heroic and Romantic were stronger for large halls. We are keen to identify the prevailing pattern in convolution reverberation to determine its definitive impact on the auditory experience.

In a follow-up study, we investigated whether the changes in emotional characteristics are relatively uniform or instrument-dependent in parametric reverberation (Anonymous 2022). We wanted to know whether parametric reverberation changes the underlying instrument space. Specifically, we aimed to discern whether the modulation of reverberation uniformly changes the emotional attributes of instruments or if certain instruments undergo more pronounced changes than others. We found that the changes in the emotional characteristics were remarkably consistent among the instruments for different reverberation amounts and lengths (Anonymous 2022).

Methodology and Listening Test

In this study, we seek to understand how the emotional characteristics of musical instruments vary with reverberation time in convolution reverberation. In our previous study on parametric reverberation, we found strong effects for Romantic and Mysterious, medium effects for Sad, Scary, and Heroic, mild effects for Happy, little effects for Shy, and the opposite effect for Comic. We are interested to determine whether this pattern holds for convolution reverberation as well, or if another pattern emerges.

To easily compare and contrast the convolution and parametric reverberation results, we conducted a listening test for convolution reverberation in the same way that we did for parametric reverberation (Anonymous 2022). Listeners compared the convolution reverberations pairwise for each instrument and emotional characteristic. Below are some of the main points, especially the differences from the parametric reverberation tests.

We tested sustained tones of recorded musical instruments in the wind and bowed string families playing isolated pitches, obtained from the University of Iowa Musical Instrument Samples (iow 2004). These sounds were all recorded in an anechoic chamber and are thus free from reverberation. Eight sustained instrument sounds were selected, namely bassoon (bs), clarinet (cl), flute (fl), horn (hn), oboe (ob), saxophone (sx), trumpet (tp), and violin (vn). These tones are 1 second long, and they were equalized by loudness by manual adjustment. The sustained instruments are nearly harmonic and have fundamental frequencies close to Eb4 (311.1 Hz).

In addition to the anechoic sounds, we compared convolution reverberated sounds with reverberation lengths of approximately 1s and 2s, which according to Hidaka and Beranek (Hidaka and Beranek 2000) and Beranek (Beranek 2004) typically correspond to small and large concert halls. To do this, we selected several representative hall convolution reverberations based on the impulse responses in Altiverb (alt 2016). We measured their reverberation lengths based on their reverberation time RT_{60} discussed in Section *Artificial Reverberation* and picked those that most closely matched the reverberation times we tested in our previous study of parametric reverberation. Table 1 shows the parametric and convolution reverberation RT_{60} values and other parameters. We also included the cathedral impulse response of King's College Chapel with a 5.44-second reverberation time to determine the effects for a more extreme case. Figures 1 to 5 show the impulse responses for the different halls we tested, along with their RT_{60} and EDT values, which were calculated by multiplying the captured time interval an impulse response takes to decay from 0dB to -10dB by 6 as discussed in Section *Artificial Reverberation*. The convolution reverberation decays were linear (in dB) from the very beginning, while the parametric reverberation decays had an immediate drop-off and shelf at -10 to -30 dB that lasted about 0.25 seconds before the linear portion of the decay commenced (see Figures 1 - 4 in (Anonymous 2022)). This reflects the presence of finely detailed and smoothly decaying early reflections in the convolution reverberation responses compared to the parametric reverberation responses. Note that the default reverberation amount (i.e., wet/dry ratio) was applied to each hall setting to faithfully replicate the room acoustics, which takes into consideration various factors, including different surfaces, that contribute to the acoustic characteristics of these venues.

Parametric					Convolution			
Hall Type and Position	Reverb Length	Reverb Amount	RT_{60}	EDT	Hall Impulse Response	Distance	RT_{60}	EDT
Small Hall Front	1s	20%	0.95	0	Royal National Theatre	8.9m	0.94	0.96
Small Hall Back	1s	80%	1.28	0	Empire Hall	10.1m	1.31	1.56
Large Hall Front	2s	20%	1.78	0	Disney Hall	14.1m	1.80	1.62
Large Hall Back	2s	80%	2.37	0	Concertgebouw Hall	14m	2.32	2.58
					King's College Chapel	20.2m	5.44	5.4

Table 1. Parametric and convolution reverberation parameters.

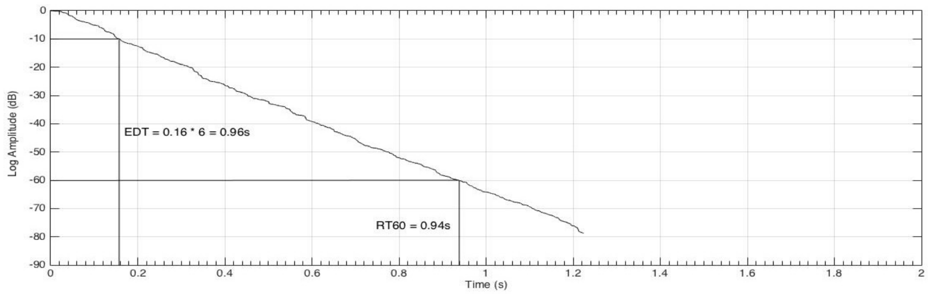

Figure 1. *Impulse response and RT_{60} for Royal National Theatre.*

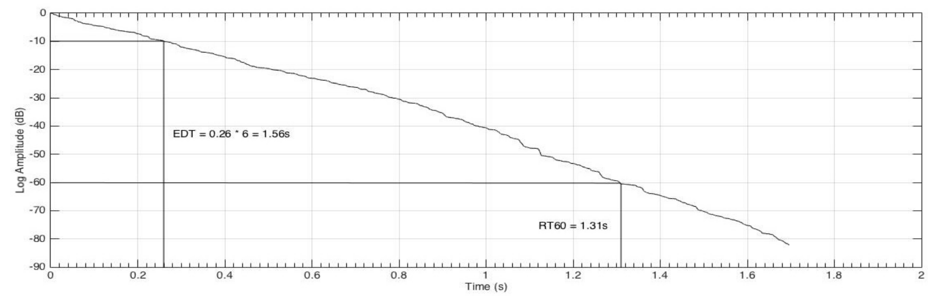

Figure 2. *Impulse response and RT_{60} for Empire Hall.*

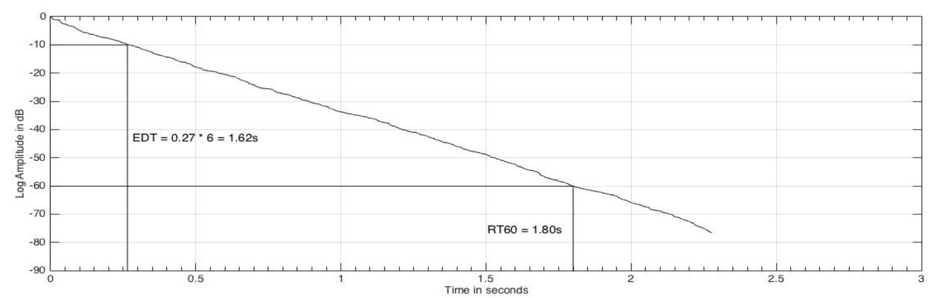

Figure 3. *Impulse response and RT_{60} for Disney Hall.*

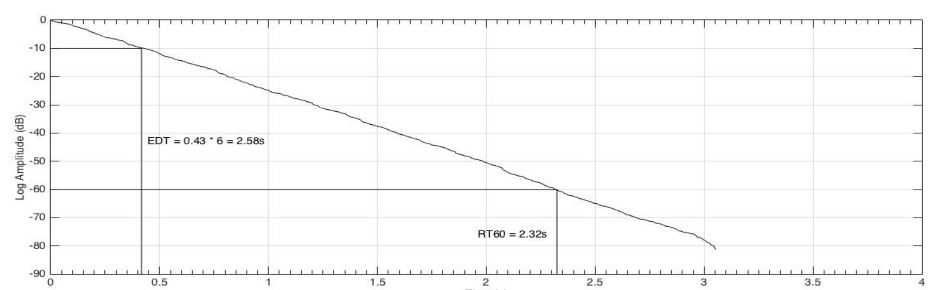

Figure 4. *Impulse response and RT_{60} for Concertgebouw Hall.*

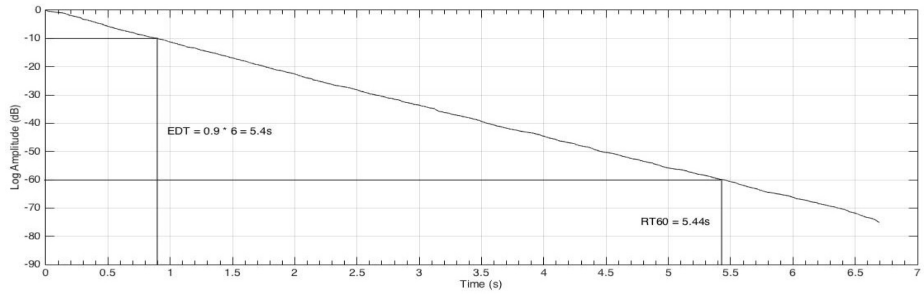

Figure 5. *Impulse response and RT_{60} for King's College Chapel.*

For this study, we tested ten emotional categories: Angry, Calm, Comic, Happy, Heroic, Mysterious, Romantic, Sad, Scary, and Shy. Some choices of emotional characteristics are fairly universal and occur in many previous studies roughly corresponding to the four quadrants of the Valence-Arousal plane (e.g., Happy, Sad, Scary/Fearful/Angry, Tender/Calm/Romantic), but there are lots of variations beyond that (Juslin and Sloboda 1993). For this study, we used the same categories that we used in our previous research on musical instruments and parametric reverberation (Wu et al. 2013, 2014c, a, b; Chau et al. 2014, 2015b; Chau and Horner 2015; Chau et al. 2015a, 2016; Chau and Horner 2016; Gilburt et al. 2016; Anonymous 2022). The ratings of the emotional categories according to the Affective Norms for English Words (Bradley and Lang 1999) are shown in Figure 6 using the Valence-Arousal model. Valence shows positiveness and Arousal shows the energy level of an emotional category. Happy, Comic, Heroic, and Romantic form a cluster, but they represent distinctly different emotional categories.

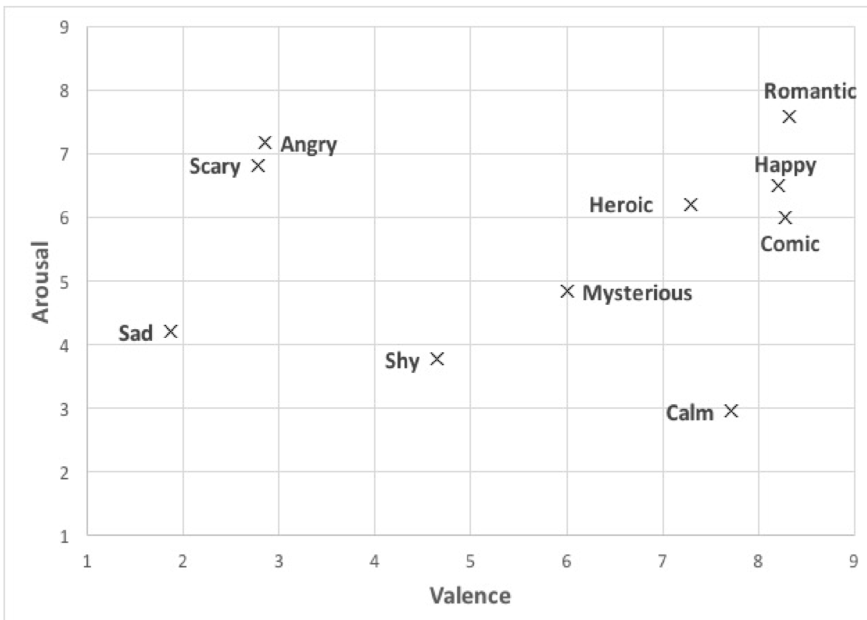

Figure 6. *Distribution of the emotional characteristics in the dimensions Valence and Arousal. The Valence and Arousal values are given in the 9-point rating in ANEW (Bradley and Lang 1999). Valence shows the positiveness of an emotional category; Arousal shows the energy level of an emotional category.*

Just before the listening test, parcipitants read online definitions of the emotional categories used in our experiment, which were taken from the Cambridge Academic Content Dictionary (cam 2022), and are shown in Table 2.

Emotional Category	Definition
Angry	Having a strong feeling of being upset or annoyed
Calm	A quiet and peaceful state or condition
Comic	Causing laughter or amusement
Happy	Glad, pleased
Heroic	Exhibiting or marked by courage and daring
Mysterious	Strange or unknown
Romantic	Relating to love or loving relationship
Sad	Affected with or expressive of grief or unhappiness
Scary	Causing fright
Shy	Disposed to avoid a person or thing

Table 2. The dictionary definitions of the emotional categories used in our experiment.

To limit the length of the test and to minimize listener fatigue, we divided listeners into two groups, where each group heard a different set of five emotional categories. We hired 72 participants to take the listening test, and since they each heard half the emotional categories, 36 participants compared each emotional category. All participants were fluent in English. They were all undergraduate students at the <Anonymous University> where all courses are taught in English. Participants were not musical experts (e.g., recording engineers, professional musicians, or music conservatory students) but average attentive listeners. Among the 72 participants, there were 51 males and 21 females. The participants ranged in age from 18 to 24. In terms of musical experience, 40 participants had some experience playing an instrument (an average of 6.3 years), and 32 participants did not have experience playing an instrument. In recruiting the participants, all indicated they had no known hearing problems.

In the listening tests, participants heard paired comparisons between the hall impulse responses for each instrument. During each trial, participants heard a pair of sounds and were prompted to choose which more strongly aroused a given emotional category (e.g., "Which tone sounds more Mysterious, 1 or 2?"). Since each trial was a single paired comparison requiring minimal memory from the participants, they did not need to remember all of the tones, just the two in each comparison. One big advantage of using paired comparisons of emotional categories is that it allows faster decision-making by the participants. Paired comparison is also a simple decision, and is easier than an absolute rating.

Each combination of two different hall impulse responses was presented for each of the eight instruments and ten emotional categories, and the complete listening test totaled $C_2^6 \times 8 \times 10 = 1200$ trials (600 trials per listener since we divided the task into two groups). For each listener, the overall trial presentation order was randomized to average out effects due to learning or fatigue. For the two sounds A and B, they heard AB where the order of A and B was random for each comparison (but if they heard AB, they did not hear BA later). The listening test took about 75 minutes, with forced short breaks every 25 minutes.

Results

For our listening test, participants compared each pair of hall impulse responses for each instrument and emotional category. Based on the listening test data (36 participants for group A, and 36 for group B), we ranked the hall impulse responses by the number of positive votes they received for each instrument and emotional category and derived scale values using the Bradley-Terry-Luce (BTL) statistical model (Bradley 1984; Wickelmaier and Schmid 2004).

For each graph, the BTL scale values for the six tones sum to 1. The BTL value for each tone is the probability that listeners will choose that hall impulse response when considering a certain instrument and emotional category. For example, if all six hall impulse responses were judged equally Happy, the BTL scale values would be $1/6 \approx 0.167$.

Figures 7 to 16 show BTL scale values and the corresponding 95 percent confidence intervals for each emotional category and instrument. Though there are certainly individual differences between instruments, for each emotional category the trend from anechoic to cathedral usually follows the same direction for all eight musical instruments. For example, Angry trends down, Calm trends up, and Shy trends up to the Disney Hall and then down. The trumpet for Mysterious was the most strongly effected among all the instruments and emotional categories with a BTL value of more than 0.5 for King's College Chapel.

We wanted to determine the number of times each hall impulse response's BTL value was significantly greater than the other five hall impulse responses over the eight instruments for each emotional characteristic. As a preliminary step, the normality of the data was calculated for each hall impulse response, instrument, and emotional characteristic. Since most of them were not normally distributed, both parametric and nonparametric statistical tests (parametric: Paired t-tests, Pearson correlation; nonparametric: Wilcoxon signed-rank tests, Spearman correlation) were used to analyze the voting data (i.e., the number of positive votes received by each hall impulse response for each instrument and emotional category). The results from the two tests showed some minor differences, but basically, they were in agreement. Table 3 shows the Wilcoxon signed-rank test results. For each hall impulse response, the maximum possible value is 40 and the minimum possible value is 0. For example, with the emotional characteristic Mysterious, the value of the King's College Chapel is 33 in Table 3 since it was statistically significantly greater than all the other hall impulse responses over all instruments in Figure 12 except for the Concertgebouw Hall in 7 instances (i.e., 40 - 7). The maximum value for each emotional characteristic is shown in bold and shaded in both tables, which are in agreement.

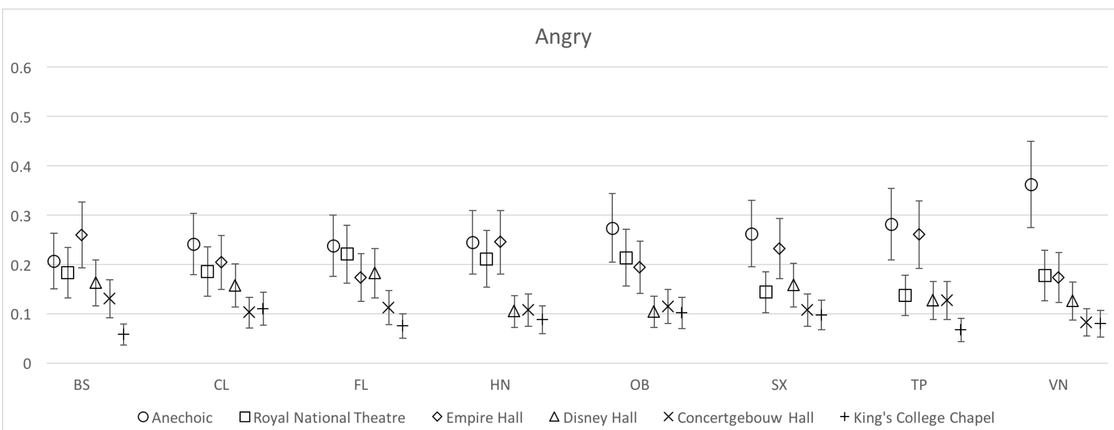

Figure 7. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Angry*

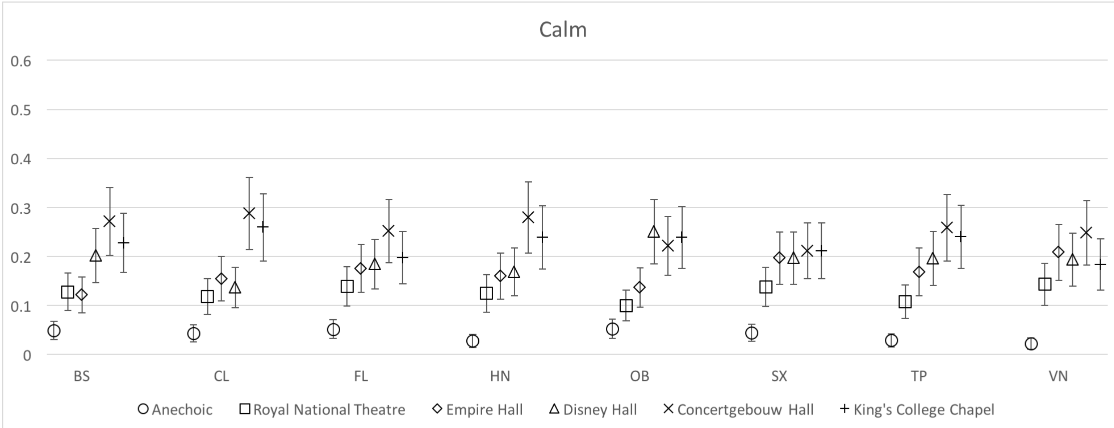

Figure 8. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Calm*

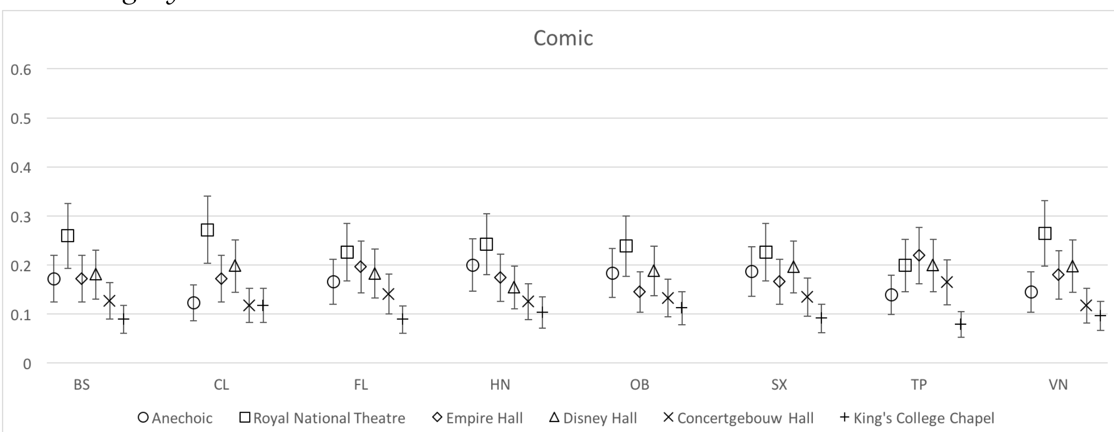

Figure 9. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Comic*

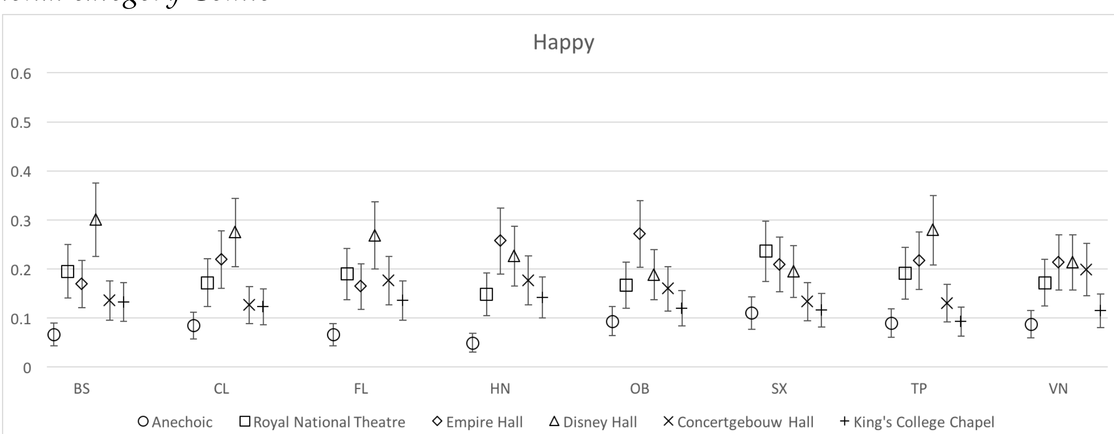

Figure 10. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Happy*

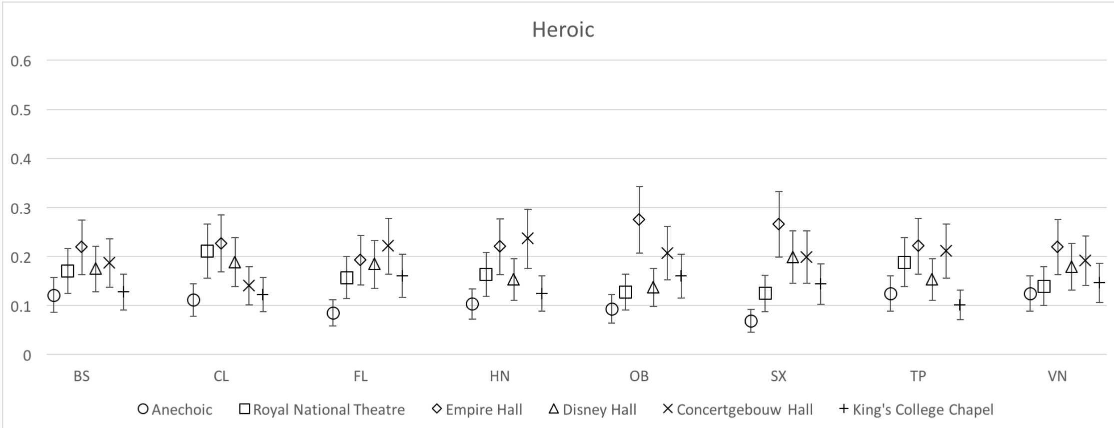

Figure 11. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Heroic*

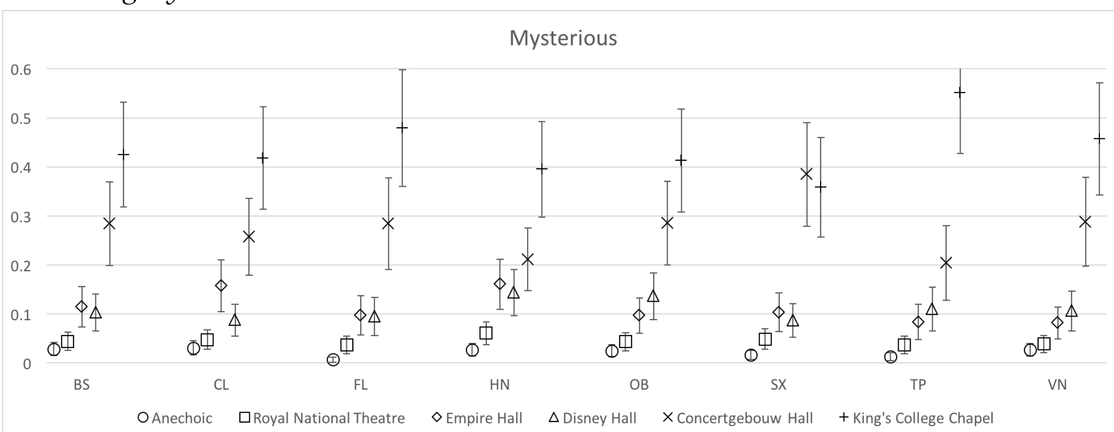

Figure 12. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Mysterious*

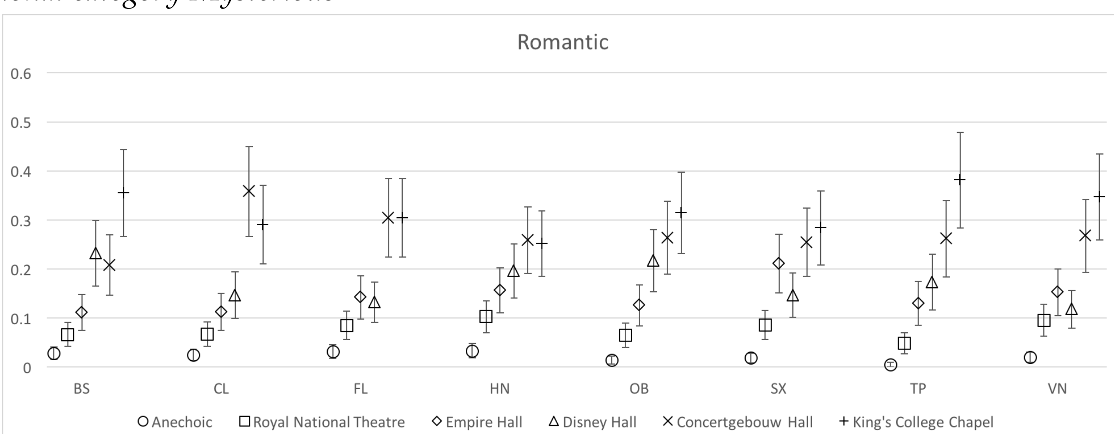

Figure 13. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Romantic*

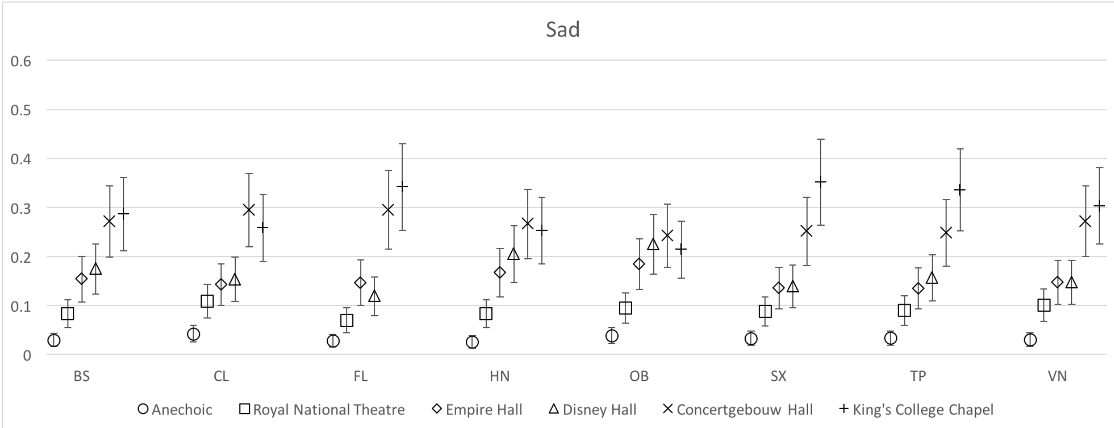

Figure 14. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Sad*

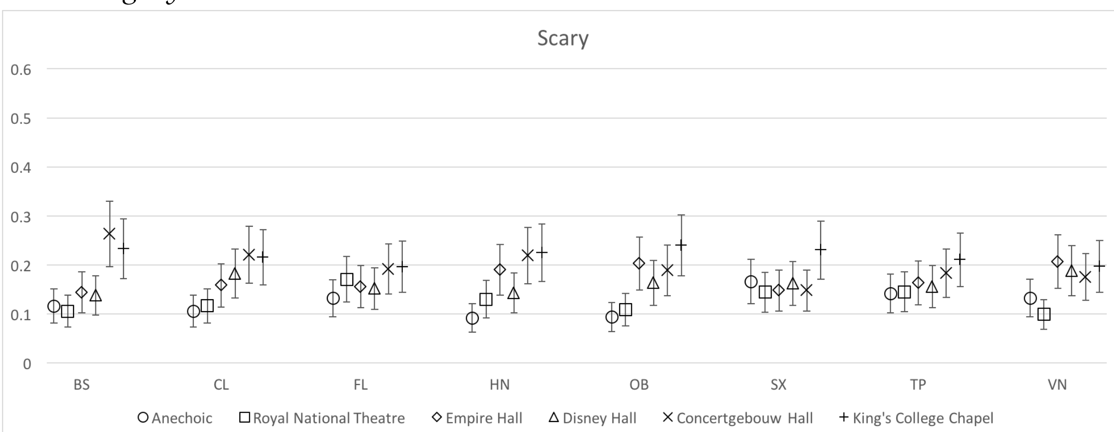

Figure 15. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Scary*

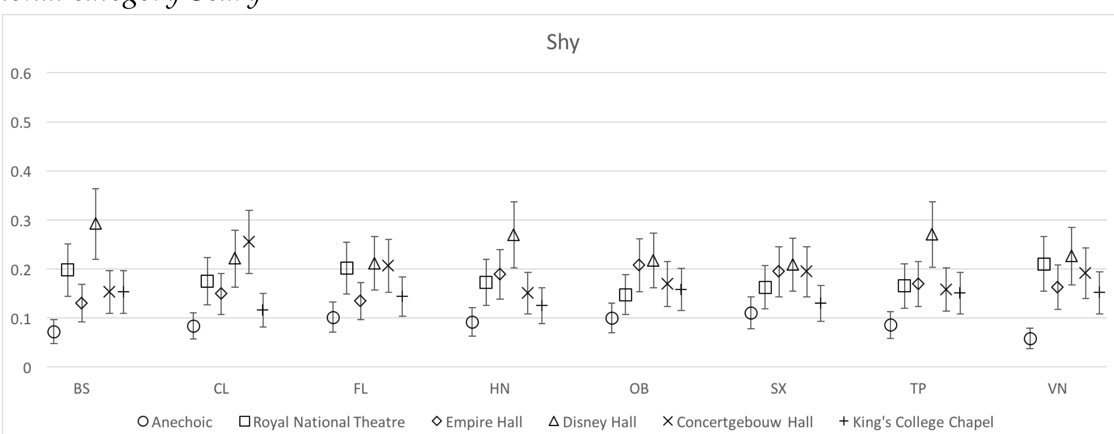

Figure 16. *BTL scale values and the corresponding 95 percent confidence intervals for the emotional category Shy*

	ANE RT_{60}=0	RNT RT_{60}=0.94	EMP RT_{60}=1.31	DIS RT_{60}=1.80	CTG RT_{60}=2.32	KCC RT_{60}=5.44
Angry	**22**	17	17	7	3	1
Calm	0	7	8	11	**19**	16
Comic	0	**15**	4	9	2	1
Happy	0	8	16	**18**	8	3
Heroic	0	4	**11**	3	5	1
Mysterious	0	4	16	16	27	**33**
Romantic	0	7	14	16	25	**27**
Sad	0	7	12	12	**25**	**25**
Scary	0	0	4	1	**9**	7
Shy	0	5	5	**13**	8	1

Table 3. Based on Wilcoxon Signed-rank tests, how often instruments had a statistically significantly greater BTL value (for $p < 0.05$) than the others for each hall impulse response and emotional characteristic

Based on Table 3, we see that halls with shorter reverberation times were the strongest for the emotional categories Angry and Comic. Halls with medium reverberation times were the strongest for Happy, Heroic, and Shy. Halls with long reverberation times were the strongest for Calm, Mysterious, Romantic, Sad, and Scary. We compared this characterization with our results from parametric reverberation (Anonymous 2022) and found agreement in seven of the eight emotional categories that we tested in that study (Heroic was the only one that was different).

As a further comparison, we correlated the BTL data from the hall impulse responses with the BTL data from our previous study of parametric reverberation (Anonymous 2022), and found a correlation of 0.74 over all emotional categories, indicating a rather remarkable level of agreement. Table 4 also shows the correlations between the results of parametric and convolutional reverberations for each emotional category. Seven of the emotional categories had significant correlations between the two studies, but Shy did not. The seven significant correlations were fairly strong ranging from about 0.47 to 0.87 for the individual categories. The emotional categories with the strongest correlations were Mysterious, Romantic, and Sad, and they also had the largest number of significant differences in Table 3.

Discussion

We were curious to see how the results for convolution reverberation would compare to the results from our previous study on parametric reverberation (Anonymous 2022). The biggest difference between them was that the convolution reverberation emotional characteristics were more pronounced. There were 62% more significant differences for the eight categories and five reverberation times that we tested in both experiments (see Table 5). This difference shows up most clearly in the emotional category Shy where there was only one significant difference for parametric reverberation and 27 for convolution reverberation.

There was also a striking basic agreement in the results. The BTL rankings for convolution and parametric reverberations were significantly and strongly correlated with a correlation coefficient of 0.74 over all emotional categories. Seven out of eight individual emotions also showed significant correlations between the two reverberation

	Pearson correlation		Spearman correlation	
Emotional Category	Correlation	P-value	Correlation	P-value
Comic	0.495	0.001	0.475	0.002
Happy	0.500	0.001	0.500	0.001
Heroic	0.607	0.000	0.521	0.001
Mysterious	0.863	0.000	0.876	0.000
Romantic	0.785	0.000	0.827	0.000
Sad	0.791	0.000	0.765	0.000
Scary	0.709	0.000	0.656	0.000
Shy	0.277	0.084	0.275	0.086
Overall	0.742	0.000	0.684	0.000

Table 4. Pearson and Spearman correlation between the BTL Values for the convolution reverberation and parametric reverberation

techniques, with correlation coefficients ranging from 0.47 to 0.87. Shy was the only category not significantly correlated since its BTL rankings were very flat for parametric reverberation.

It was unexpected that the emotional characteristics Angry and Scary, which have near-identical Valence and Arousal values (see Figure 6), were so opposite in their results (see Table 3). Angry was the strongest for halls with short reverberation times, and Scary was the strongest for halls with long reverberation times. The Scary results agree with our previous parametric reverb results (Anonymous 2022), as well as the results by Västfjäll et al. (Västfjäll et al. 2002) and Tajadura-Jiménez et al. (Tajadura-Jiménez et al. 2010), who found that larger reverberation times and larger rooms were more unpleasant.

Similarly, the emotional characteristics Comic, Happy, Heroic, and Romantic all have similar Valence and arousal values (see Figure 6), yet they showed distinctly different results in Table 3. Comic, Happy, and Heroic were the strongest in halls with short and medium reverberation times, though their patterns were distinctly different. Romantic was in a different class altogether and was very strong for long reverberation times. The results of Västfjäll (Västfjäll et al. 2002) and Tajadura-Jiménez

Emotional Category	Parametric	Convolution
Comic	15	8
Happy	9	36
Heroic	12	16
Mysterious	49	65
Romantic	42	64
Sad	29	59
Scary	21	14
Shy	1	27
Total	178	289

Table 5. Number of significant differences for eight emotional categories and five reverberation times. Angry and Calm were not included in our previous experiment, while the 5.44s Cathedral reverb time was not tested in our previous experiment.

(Tajadura-Jiménez et al. 2010) suggested all four of these characteristics would be stronger in smaller rooms, but Table 3 shows the differences between these emotional characteristics. For example, Table 3 shows that Happy was the strongest in the medium-sized Disney Hall.

In a sense, the columns of Table 3 represent the “footprints" of emotional characteristics of the individual halls relative to one another. The Anechoic Chamber was singularly Angry in its response, while the crisp sound of the Royal National Theatre was strong for Angry and Comic. The hard bright surfaces of the Empire Hall brought out emotional characteristics such as Angry, Happy, and Heroic. The warm sound of Disney Hall was especially unique in bringing out Shy and Happy. The sophisticated elegance of the Concertgebouw Hall was apparent in the categories of Calm, Mysterious, Romantic, and Sad with a touch of Scary. Finally, the spacious King’s College Chapel also brought out the characteristics of Mysterious, Romantic, and Sad. The first two are even a bit more than the Concertgebouw Hall with the King’s College Chapel’s 5-second reverberation time.

So, to what extent do the data in the columns of Table 3 represent the particular colorings of these halls as compared to the general characteristics of a generic concert hall with these reverberation times? In other words, how particular or general are these footprints of emotional characteristics? The answer is: we don’t know for sure at this stage. However, the strong agreement between the convolution and parametric reverberation results already suggests that the trends emerging in the two studies are indicative of how the underlying emotional characteristics change with reverberation time. Within these trends, the colorations of the particular halls may bring out individual emotional characteristics such as Comic, Happy, Heroic, or Shy, reflected by the insignificance of correlation we can see in Table 4.

Conclusion

The main goal of our investigation was to see how the emotional characteristics of musical instrument tones changed with reverberation time in convolution reverberation. Based on Table 3, our main findings are the following:

1. Halls with shorter reverberation times tended to emphasize the emotional characteristics Angry and Comic.
2. Halls with medium reverberation times tended to emphasize the emotional characteristics of Happy, Heroic, and Shy.
3. Halls with longer reverberation times tended to emphasize the emotional characteristics of Calm, Mysterious, Romantic, Sad, and Scary.

While the effects on the emotional characteristics were more pronounced in convolution reverberation compared to parametric reverberation, a strong agreement between the parametric and convolution reverberation results can be found in Table 4. These strong correlations indicate that reverberation time has a remarkably consistent effect on the emotional characteristics regardless of whether using convolution or parametric reverberation. It makes sense that these two different processes would have some deep underlying similarities since they are both reverberation techniques. It also makes sense that convolution reverberation would have a more pronounced effect on the emotional characteristics since convolution reverberation is often regarded as warmer, more natural, and smoother than parametric reverberation, which is often regarded as blander in comparison.

This work, together with our parametric reverberation study, offers a definitive perspective for both audio engineers and musicians on how reverberation could be used to bring out specific emotional characteristics in musical instrument sounds. Going further, it would be possible to re-run the same experiment on three or more halls for each of the five levels of reverberation times we tested in the paper to determine the general trends and isolated differences. This would provide more conclusive results. Another possible future work is to investigate different reverberations such as spring reverberation, and see whether they will have similar effects on perceived emotional characteristics as we have seen in the parametric and convolution reverberation studies.

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