

## Research article

# Prediction bias for physical exertion in chronic fatigue: Evidence from an observational paradigm

Vallilath V.M. Ramakrishnan<sup>a</sup>, Yakeen Hafouda<sup>a</sup>, Joe Butler<sup>b</sup>, Paul Mullins<sup>a</sup>, Hans-Peter Kubis<sup>a,\*</sup>

<sup>a</sup> School of Psychology and Sport Science, College of Medicine and Health, Bangor University, UK

<sup>b</sup> School of Psychology, University of Sunderland, UK

## ARTICLE INFO

## Keywords:

Fatigue  
Perception of effort  
Chronic fatigue  
Prediction bias  
Exercise

## ABSTRACT

Many clinical conditions are associated with a high incidence of chronic fatigue. While some physiological causes for chronic fatigue are established, e.g., processes connected to inflammation, psychological factors may also contribute. The metacognitive theory of dyshomeostasis proposes that a mismatch between cognitive predictions and sensory evidence for actions undermines self-efficacy and perception of control, contributing to chronic fatigue. We aimed to investigate alterations in prediction for physical exertion in participants with chronic fatigue using a new paradigm based on observation, therefore avoiding sensory feedback from the periphery. Participants watched randomised sets of videos with people exercising at different physical exertion levels. Participants had to predict the rate of physical exertion (RPE) of the individuals observed in the videos. Additionally, questionnaires for chronic fatigue, disability, mood, clinical history and body characteristics were assessed. 49 complete data sets from participants with chronic fatigue and 74 data sets from control subjects were analysed in this study. Compared with the control group, participants with chronic fatigue predicted a significantly higher RPE for the observed exercising individuals across all exertion levels. Multiple linear regression models revealed that in the control group, the variance of the bias in the prediction of exertion was significantly explained by the characteristics of the individuals observed in the videos. However, in the chronic fatigue group, the variance of bias in the prediction of exertion was strongly explained by the characteristics of the observer, i.e. fatigue levels and disability. Outcomes revealed that participants with chronic fatigue predicted higher exertion levels during observations and that levels were strongly influenced by their clinical symptoms, suggesting a prediction bias for exertion being present even without performing physical tasks.

## 1. Introduction

Fatigue can be defined as the decreased ability and efficiency in performing physical and/or mental tasks, caused by former activities, diseases, or syndromes. Chronic fatigue that is not alleviated after rest or recovery, unlike acute fatigue, but sustains over long periods, i.e., at least 6 months [1]. It is often perceived as an overwhelming sense of tiredness, lack of energy, or feeling of exhaustion [2]. Many clinical conditions reveal a high incidence of chronic fatigue; more than 80 % of Rheumatoid Arthritis patients experience some form of fatigue [3], and in about 78 % of Obstructive Sleep Apnoea patients [4], and fatigue in COVID-19 patients has a prevalence of 28 % two years after infection [5]. In many neurological conditions like Multiple Sclerosis (MS), stroke, traumatic brain injuries, and Parkinson's disease, fatigue reaches

high severity levels, disabling individuals in their daily life activities [6–9]. In Myalgic Encephalopathy/Chronic Fatigue Syndrome (ME/CFS), chronic fatigue is the hallmark of the syndrome, with often catastrophic impact on sufferers [10,11].

Underlying causes of chronic fatigue are extremely variable, arising from both physiological and psychological factors. Depending on the clinical condition, contributions of inflammatory factors [12], neuro-inflammation [13], brain lesions [14], impaired neurovascular coupling [15], impaired mitochondrial/metabolic function [16,17], oxidative stress [18], and autonomic nervous system dysfunction [19,20] are all suggested as physiological mechanisms contributing to fatigue. Psychologically, fatigue is often linked to chronic stress, anxiety and depression affecting both cognitive functioning and emotional regulation, leading to a state of exhaustion [21]. Functional Magnetic

\* Corresponding author.

E-mail address: [h.kubis@bangor.ac.uk](mailto:h.kubis@bangor.ac.uk) (H.-P. Kubis).

<https://doi.org/10.1016/j.bbr.2026.116043>

Received 8 July 2025; Received in revised form 18 December 2025; Accepted 12 January 2026

Available online 15 January 2026

0166-4328/© 2026 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Resonance Imaging (fMRI) studies, investigating functional alteration of brain areas in chronic fatigue patients, suggest distinct activity alterations in brain areas and their impaired connectivity are correlated with measures of fatigue [15], in particular, the cortico-striatal network [22] and temporal parietal junction [23] in studies focusing on cognitive fatigue paradigms. While task-based fMRI studies reveal activity and connectivity alterations in specific patient groups such as MS, CFS, and Parkinson's disease, the overarching changes across conditions remain poorly understood.

Furthermore, beyond physiological changes, involvement of maladaptive learning and conditioning has been proposed to play a role in chronic fatigue, with theoretical models developed to explain their contribution, as well as studies providing support. As an example, the Co-conditioning Theory of Chronic Fatigue [24] proposed that central sensitisation and classical conditioning of central inhibition, due to repeated fatigue assaults, could contribute to chronic fatigue. Indeed, experimental studies, using a classical conditioning paradigm, revealed that conditioning could lead to enhanced fatigue perception in healthy participants performing cognitive and physical tasks [25,26]. A further model suggests that associative learning processes could facilitate the trajectory from short-term to chronic fatigue in clinical conditions like CFS. Fatigue becomes the conditioned response triggered by stimuli that formerly were paired with fatigue [27]. While the former theory focused on conditioning processes in relation to periods of experiencing fatigue, Dobryakova et al. [22] proposed a contribution of effort-reward imbalance as a central feature for cognitive fatigue. Coincidentally, a positive association of chronic fatigue with effort-reward imbalance is found in individuals with fatigue symptoms [28].

Furthermore, the metacognitive theory of dyshomeostasis proposed that disease-induced fatigue is a result of a mismatch between prior cognitive predictions and ascending sensory evidence undermining individuals' perceptions of control, mastery and self-efficacy for activity [29]. Likewise, Greenhouse-Tucknott and colleagues [30] proposed that fatigue results from a loss of certainty or confidence in anticipatory control over actions caused by repeated prediction errors related to effort perception for tasks. These former processes could impact the coupling of prediction with action, such that the assessment of an "optimal" action, based on the affordance of an object in the environment and the individual's inherent capacities, is impaired, resulting in a predisposition towards fatigue [29,31,32].

Consequently, higher prediction of effort for a task might arise from conditioned/learned experience of effort, which could be connected with higher sensitisation of the inhibition system [33]. The process for this higher sensitisation might arise from an upregulation of afferent signals for effort evaluation while planning a task, stronger effort evaluation of the afferent signal within the effort-reward evaluation, or reduced reward prediction. For investigating the problem of elevation of effort prediction for a performed task, it is difficult to differentiate between physiological/neurological influences on central sensitisation and learned/conditioned contributions. Paradigms which rely on trained or formerly experienced tasks, cognitive or physical, may contain physiological and neurological influences on central sensitisation in their assessment [34]. While many investigations focused on cognitive effort and fatigue [35], research on physical effort is also needed due to the impact of chronic fatigue on daily activities. Individuals with chronic fatigue demonstrate an elevated effort rating during exercise when compared with healthy individuals [36], even when discrepancies between healthy and chronic fatigue individuals, like cardiometabolic reactions, become non-significant after adjusting for physical fitness levels [37].

In theory, investigating central prediction bias of physical efforts involved in observed actions would avoid the afferent feedback problems and would potentially reveal a general tendency for elevated effort prediction in participants with chronic fatigue compared with controls, without afferent signals (peripheral or central). But for this to be tested, individuals need to have the general capability to predict effort/exertion

when observing an individual. While perception of effort refers to the amount of mental or physical energy being given to a task [38], relying primarily on central response, perceived exertion integrates peripheral feedback from the body whilst exercising [39,40].

Indeed, a strong correlation between observer and participant rate of perceived exertion (RPE) ( $r = 0.79-0.84$ ) was found when individuals observed and predicted the RPE of exercising (walking, running) individuals [41]., individuals were able to gauge the level of effort exerted by an exercising individual through visual cues such as facial grimaces and eye squints [42]. Muscle activity in facial muscles measured by electromyography (EMG) during exercise was found to have a significant positive correlation with RPE ratings [43], revealing the availability of visual cues for effort/exertion prediction in observed individuals.

The process of judging/predicting the exertion of an observed individual includes using visual information, as mentioned above, for inferring an internal state, effort/exertion, from observation. In this process, brain areas which are used for own effort prediction might be activated. In other contexts, it has been shown that people can integrate visual observations into body sensations, i.e., rubber-hand illusion [44, 45] and that brain networks, like the mirror-neuron system and others, are responsive to not only observations of motor actions [46,47] but also visual imagery [48]., The observation of painful stimuli in others activates distinct brain areas, which are also activated when receiving painful stimuli, reflecting affective responses [49].

The investigation of the prediction of effort/exertion through observation would be informative across clinical conditions, establishing a shared functional change in chronic fatigue symptoms.

Our study investigated the prediction of effort/exertion by observation in individuals with ( $n = 49$ ) and without chronic fatigue ( $n = 74$ ). Participants watched a set of videos of individuals with various levels of physical fitness running at different speeds on a treadmill. Participants were asked to rate the effort/exertion of the observed individuals under the conditions watched, rating the rate of perceived effort/exertion (RPE) on a 6–20 Borg scale [50]. In addition, participants were asked to focus on a photo of a standard staircase and predict their own RPE using the same scale if they were to climb the stairs. Psychological questionnaires, the fatigue assessment scale, and clinical information were also collected.

We first hypothesised that both individuals with chronic fatigue and control participants would be able to predict the perceived effort/exertion of the exercising individuals, revealing a moderate to strong correlation between the RPE provided by the individuals in the videos and the predicted RPE given by the participants watching the videos.

Secondly, we hypothesised that individuals with chronic fatigue would rate the RPE of the exercising individuals in the videos consistently higher than the controls, revealing a central bias towards higher effort prediction consistent with an assumption of a higher sensitisation of the inhibition system [33]. These hypotheses are not mutually exclusive; while both groups may predict a perceived effort/exertion (H1), the CFG will consistently predict higher absolute RPE values when compared to HG (H2).

Thirdly, we hypothesised that the bias in RPE prediction (deviation between the given RPE by the exercising individuals and the RPE predicted by observers) would be associated with the reported fatigue score of the chronic fatigue individuals. A stronger influence of one's own chronic fatigue experience should influence predictions for effort/exertion, even for observed actions, if a metacognitive process is critical in the chronic fatigue development across clinical conditions [29,30].

## 2. Materials and methods

### 2.1. Ethical approval

Both studies were given ethical approval by the Bangor University School of Human and Behavioural Sciences Ethics Committee (ethics

number study 1: 2021–17055, study 2: 2022–17197) in accordance with the Declaration of Helsinki.

## 2.2. Participants

### 2.2.1. Sample size calculation (Study 1)

Based on the findings of Gallagher et al. [41], which reported a strong correlation ( $r = 0.80$ ) between observer and participant RPE, an initial power analysis indicated that a minimal sample size of 10 participants would be required. However, given the simplicity of the study design in Gallagher et al. [41], this effect size is likely to be an over-estimation. To ensure a more conservative and generalizable estimate, we adopted a more moderate correlation coefficient ( $r = 0.60$ ). Using this adjusted effect size, along with an alpha level of 0.05 and a beta level of 0.20 (corresponding to a power of 80 %) in sample-size.net [51], a revised sample size calculation yielded a minimum requirement of 19 participants.

### 2.2.2. Sample size calculation (Study 2)

For the chronic fatigue cohort, the sample size estimation was based on the mean and standard deviation of the predicted RPE bias observed in the healthy participants. Using an estimated effect size of 0.4, an alpha level of 0.05, and a beta level of 0.20 (corresponding to a power of 80 %), an a priori power analysis in G\*Power 3.1.9.7 [52] indicated that a sample size of 43 participants would be required to detect a significant difference in an ANCOVA for predicted RPE.

**Study 1 (healthy individuals):** Healthy participants were recruited via online advertisements on social media and paper advertisements from the Bangor University student population, as well as from the general public using social media advertising. **Inclusion criteria:** healthy male and female subjects,  $\geq 18$  years, were eligible for participation. **Exclusion criteria:**  $< 18$ , a clinical diagnosis of chronic fatigue and/or a medical condition that prevented him/her from walking were excluded from the study. Complete data sets from  $N = 74$  participants were used for analysis;  $n = 23$  incomplete data sets were excluded from the study.

**Study 2 (individuals with chronic fatigue):** Participants with chronic fatigue were recruited via social media advertisements from self-help groups on social media for obstructive sleep apnoea (OSA), chronic fatigue syndrome/myalgic encephalomyelitis (CFS/ME), rheumatoid arthritis (RA), multiple sclerosis (MS), chronic kidney disease (CKD), Heart Failure (HF) and Long Covid (LCOVID). **Inclusion criteria:** Male and female participants,  $\geq 18$  years, with a confirmed clinical diagnosis of chronic fatigue, were eligible for participation. **Exclusion criteria:**  $< 18$ , without a clinical diagnosis of chronic fatigue, or unable to walk.  $N = 49$  complete data sets from participants were used for analysis;  $n = 22$  incomplete data sets were excluded from the study.

The exclusion criterion ‘unable to walk’ was included because one of the study tests (in Study 1 and 2) required an imagined stairway climb, which could be potentially influenced by a lack of prior walking experience. Participants were cognitively sound and demonstrated adequate comprehension and understanding of the RPE scale during the task familiarisation procedure.

In both studies, advertisements on social media and posters contained a link to a separate Qualtrics-based webpage with additional study details and participant study information. Informed consent for participation was acquired on the last page of the electronic document. Participants who consented gained access to the respective remote study on Qualtrics (study 1 or 2).

As an incentive for taking part, participants of both studies were offered entry into a prize draw to win an iPad after participation. However, this is unlikely to have influenced their RPE predictions as the task involved no performance-based reward.

## 2.3. Study design

Both studies ran using a Qualtrics platform, embedding bespoke video/image tasks and questionnaires. Study structures are depicted in Fig. 1.

## 2.4. Measures

### 2.4.1. Body characteristics and clinical history

Participants in both studies were asked to provide their age, sex, ethnicity, height, and weight. Additionally, participants with chronic fatigue in Study 2 were also asked about their clinical history, i.e., chronic disease(s), how long since they had been diagnosed, and for how long they had chronic fatigue problems.

### 2.4.2. Questionnaires

Self-report questionnaires were integrated into the Qualtrics studies in the order presented in Fig. 1.

**2.4.2.1. Positive and negative affect schedules.** (PANAS) [53] measures positive and negative mood states over a one-week period using two 10-item scales; Cronbach's alpha values of 0.89 for positive and 0.85 for negative affect [54] (For Study 1 (HG) Cronbach's alpha values for positive and negative affect were 0.68 and 0.69 and for Study 2 (CFG) Cronbach's alpha values for positive and negative affect were 0.67 and 0.63).

**2.4.2.2. Fatigue assessment scale (FAS).** [55] evaluates symptoms of fatigue using a 10-item self-report scale. Score levels can be divided into two sub-categories: physical and mental fatigue. Subjects choose from a five-point Likert scale: 1 =never to 5 =always in response to statements. Sum scores reflecting the severity of fatigue levels: i.e. ( $< 22$  indicates ‘normal’ fatigue levels; 22–34 indicates mild-moderate fatigue;  $\geq 35$  indicates severe fatigue) [56]. The FAS has strong internal consistency (Cronbach's alpha 0.9) and is widely used for self-reported assessment of fatigue in chronic diseases [55,57] (For Study 1 (HG), Cronbach's alpha 0.92 and for Study 2 (CFG), Cronbach's alpha 0.91).

**2.4.2.3. Lawton-Brody activities of daily living.** (LADLS) assesses the daily functional status of an individual using an 8-item scale.  $CR\alpha$ : 0.94 [58] (For Study 2 (CFG), Cronbach's alpha 0.70). The independence of the following domains is scored: ability to use a telephone, shopping, food preparation, housekeeping, laundry, mode of transportation, responsibility for own medications, and handling finances [59]. A higher total score corresponds to a higher level of functional status and independence.

**2.4.2.4. National aeronautics and space administration physical activity rating.** (NASA PAR) Scale [60]. The scale categorises physical activity into five different levels from 1 (little or no activity) to 5 (brisk walking, jogging, or running for more than 3 h per week).  $R = 0.78$ – $0.81$  [61].

**2.4.2.5. Cardiorespiratory fitness.** (CRF) levels of healthy subjects (study 1) were estimated using the protocol by Jurca et al. [60], which provided a non-exercise estimation of cardiorespiratory fitness CRF is estimated with high cross-validity,  $R = 0.81$ . Sex, age, BMI, resting heart rate (RHR), and score of NASA-PAR were used for predicting metabolic equivalents (MET). Resting heart rate (RHR) was measured using the ‘Instant Heart Rate’ app (<https://apps.apple.com/us/app/instant-heart-rate-hr-monitor/id409625068>), downloaded by participants. The IOS and the Android versions of the app have high test-retest reliability and intraclass correlation coefficient (ICC: 0.76 and ICC: 0.82), respectively [62]. Participants were asked to ensure that they had not engaged in vigorous exercise within an hour, that they had not ingested any caffeine within 2 h, and that they had a minimum 3-hour interval before their

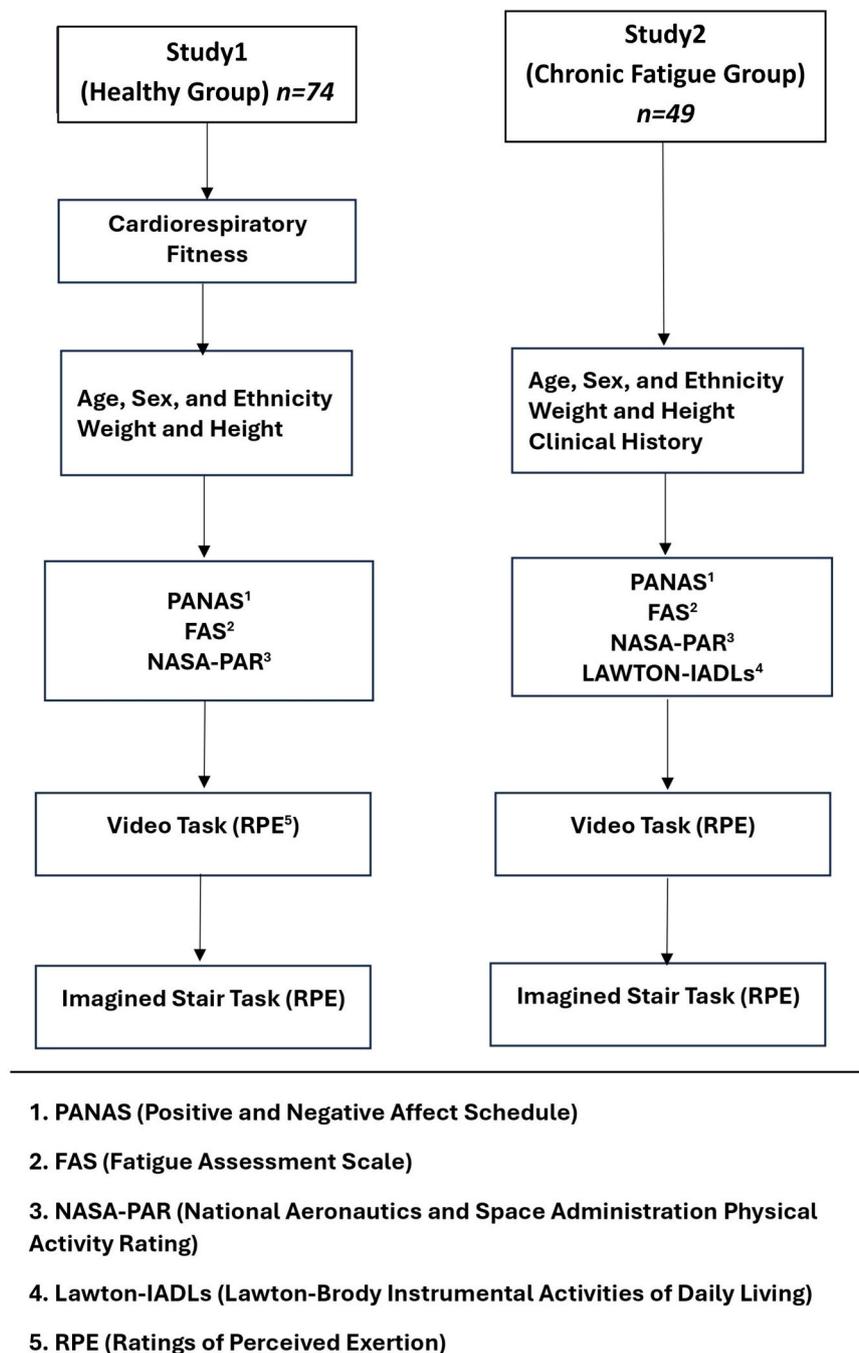


Fig. 1. Study design and procedure flowchart for healthy group (HG) (Study 1) and chronic fatigue group (CFG) (Study 2).

last meal before measuring RHR.

**2.4.2.6. Ratings of perceived exertion.** (RPE) 6–20 scale [63] was used throughout in both studies. Scales were presented in the video task and image task on a VAS scale with verbal statement and numeric scores visible (see below). The RPE scale was introduced and appropriately anchored with example statements before each task. 6: no exertion at all, 20: maximal exertion (Fig. 2) (see supplementary file for details).

**2.4.2.7. Exercise videos.** Videos for the observed effort task were embedded in the studies on Qualtrics (Fig. 2). The videos were based on filming five healthy volunteers with varied fitness, age, sex, and race. Individuals were filmed exercising on a treadmill at various speeds (4 km/h; 8 km/h; 10 km/h; 12 km/h; 14 km/h) for three minutes each,

starting at the lowest speed after warm-up. Heart rate was recorded throughout, and individuals were asked to rate their exertion at each speed during the last minute of each stage using the Borg Rating of Perceived Exertion (RPE 6–20) scale [64]. Videos captured the individuals from the front (head and chest) to enable maximal recognition of facial expressions related to physical effort [43], as well as from the side with a whole-body view for judgment of movement. No information about the speeds of the treadmill was given in the videos (Fig. 2). Table 1 summarises the individuals' characteristics (age, sex, and ethnicity), as well as their RPE and heart rate per speed as a measure of their cardiovascular fitness.

Both studies used the same exercise videos. The last 30 s of the 3-minute stages were selected due to this section being associated with RPE and heart rate measures. The necessary length of the videos for



Move the slider to indicate how hard you think the person in the video was exercising



**Fig. 2.** Video snapshot and RPE rating interface used in the observational exertion task. The figure shows an example of the video paradigm used in our experiment. Two video frames of a subject exercising on a treadmill, used in the observational exertion task. The left panel shows a front-facing view to capture facial expressions, while the right panel presents a side view for assessing gait and body movement during treadmill exercise. Below the video frame is the Ratings of Perceived Exertion (RPE) interface used by participants to predict the exertion level of the exercising individual. The RPE was recorded on a Borg scale ranging from 6 ("No exertion at all") to 20 ("Maximal exertion"). Participants moved a slider to register their perceived exertion estimate after each video. The person depicted agreed to being identifiable in the publication.

**Table 1**  
Video recording subjects characteristics.

	Subject1	Subject2	Subject3	Subject4	Subject5
<b>Age (yrs.)</b>	25	42	59	25	23
<b>Gender</b>	Male	Male	Male	Female	Female
<b>Ethnicity</b>	White	White	White	Arab (Other)	White
<b>Ratings Of Perceived Exertion (6–20)</b>					
<b>Speed</b>					
4 km/h	6	7	6	6	6
8 km/h	8	9	8	10	7
10 km/h	12	10	10	12	11
12 km/h	14	12	12	16	14
14 km/h	18	15	14	20	19
<b>Exercising Heart Rates (bpm)</b>					
<b>Speed</b>					
4 km/h	87	80	64	100	95
8 km/h	150	128	111	162	143
10 km/h	175	157	125	174	162
12 km/h	193	169	138	189	178
14 km/h	201	180	150	195	189
<b>HR per Speed (bpm/km/h)</b>					
	49.24	44.27	35.67	72.87	62.13

judging the RPEs of the exercising individuals by observation was examined in a pilot with healthy volunteers, who needed a maximum of 15 s to make a judgment on RPE. To accommodate the potential influence of chronic fatigue on observations, the time of the video clips was set to 30 s each for all participants in both studies. No participant indicated any lack of time to make a judgment regarding RPE.

Within each study, the clips were presented in five randomised blocks of five videos of the exercising individuals at the same speed; within each speed block, the order of the videos of the individuals

exercising was randomised as well. Participants consequently viewed a total of 25 videos, organised into 5 randomised speed blocks, each containing 5 videos of different individuals exercising at the same speed in random order. Participants, after being introduced to the RPE measure and anchoring of the scores before watching the videos, watched each of the video clips and were then asked to submit an RPE score to rate the amount of effort/exhaustion they thought the individuals would perceive (precise information about the study material, see supplementary file). Participants received a brief orientation (embedded in Qualtrics) on how to base their judgment of RPE on the visible facial and movement cues of the individual exercising in the video. The RPE score was determined by using a slider on screen with anchor points and scores displayed on a VAS scale, RPE 6–20 (see Fig. 2). Subjects could only adjust the RPE after the video clip finished and could only progress to the next video after they had adjusted the slider to a new position. The slider was always resting at RPE 6 at the beginning of all videos. A block-wise structure was used to isolate the effort/exertion levels based on speed; hence, variations in RPE bias between groups were analysed across these blocks.

**2.4.2.8. Imagined stair task.** After the video task, participants were asked to imagine walking up a staircase with 12 steps depicted in a photo (Fig. 3). The task was based on a study by Warren et al. [65] that showed people were able to judge their own ability and effort using images of a staircase. Participants were asked to visualise themselves walking up these steps and rate their level of effort/exertion using the RPE slider VAS scale provided. It was presented after the exercise videos to make sure that there were no priming effects on RPE predictions during the video task. All participants observed the identical standardised image of the staircase, which ensured uniformity in viewing



**Fig. 3.** Staircase image used in the imagined exertion task. The figure displays the standardised image of a 12-step wooden staircase shown to participants during the imagined exertion task. Participants were instructed to visualise themselves ascending the stairs and to rate the perceived level of effort using the Borg 6–20 Ratings of Perceived Exertion (RPE) scale.

perspective and removed any variability in visual context.

**2.4.2.9. Data analysis.** All variables were tested on assumptions for parametric testing and tested accordingly with *t*-tests, ANOVA, and ANCOVA; parameters which were not normally distributed were analysed using non-parametric testing, i.e. Chi-square test, Mann-Whitney *U*-test, and Kruskal-Wallis' test. ANCOVA analysis compared the predicted RPE values of HG and CFG groups using the experienced RPE values as a covariate. Spearman's correlation analysis was used to examine the relationship between experienced RPE, predicted RPE, RPE bias, imagined Stair task and FAS scores in both groups. Separate multiple linear regression analyses were run for HG and CFG using observed-person characteristics (speed, age, sex, ethnicity, HRperSpeed) and observer characteristics (speed, age, sex, ethnicity, BMI, NASA-PAR, Stair RPE, LADLS, FAS, CRF if applicable) using the Enter method of selected parameters. Group comparisons for the Stair RPE and the questionnaire data used an independent *t*-test or Mann-Whitney *U*-test as appropriate. Used tests are indicated in the result section. The data is shown in mean and standard deviation, as well as median and 25th and 75th percentiles. Significance level was set at  $p < 0.05$ . The Statistical Package for Social Sciences (IBM SPSS) version 27 was used to examine the data.

In this study, the terms 'experienced RPE' and 'predicted RPE' will be used consistently; 'experienced RPE' refers to the RPE provided by the volunteers exercising in the videos, while 'predicted RPE' refers to the RPE reported by the healthy participants and participants with chronic fatigue watching the videos. 'Bias' was calculated by subtracting the experienced RPE from the predicted RPE, as shown in the equation below.

$$\text{Bias} = \text{predicted RPE} - \text{experienced RPE}$$

### 3. Results

#### 3.1. Participants

For the group of healthy participants (HG), we obtained 99 datasets; of these, 25 datasets were incomplete and excluded from analysis. Seventy-four complete datasets were included (females: 61 %  $n = 67$ ;

*Mdn* age: 30.00 years (PCTL25, 75: 21.00, 43.00)). Seventy-eight datasets were collected from individuals with chronic fatigue (CFG); 29 datasets were excluded due to being incomplete, leaving 49 complete datasets to be included in the final analysis (females: 80 %  $n = 39$ ; *Mdn* age: 54.00 years (PCTL25, 75: 41.00, 65.00)). Characteristics of individuals are shown in Table 2. Individuals in the CFG (*Mdn* age: 54.00) were significantly older than individuals in the HG (*Mdn* age: 30.00),  $U = 573.50$ ,  $p = .000$ . In HG, 69 % ( $n = 51$ ) were white British, 61 % ( $n = 45$ ) were female, and 39 % ( $n = 29$ ) were male. In CFG 84 % ( $n = 41$ ) were white British, 80 % ( $n = 39$ ) were female, and 20 % ( $n = 10$ ) were male. NASA physical activity scores were significantly lower for CFG ( $M = 1.49$ ,  $SD = 0.82$ ) than HG ( $M = 3.24$ ,  $SD = 1.49$ ),  $X^2(1, N = 104) = 37.55$ ,  $p = .000$ . Individuals of CFG had significantly higher BMIs ( $M = 29.84$  kg/m<sup>2</sup>,  $SD = 6.70$ ) than HG participants ( $M = 25.74$  kg/m<sup>2</sup>,  $SD = 6.44$ ),  $t(109) = -3.235$   $p = 0.002$ .

#### 3.2. Medical conditions and characteristics in chronic fatigue participants

Table 3 summarizes the medical conditions and characteristics of CFG participants. ME/CFS was the most frequent medical diagnosis ( $n = 17$ ), followed by Long COVID ( $n = 13$ ). In addition, five patients were diagnosed with OSA and four patients with RA, while three patients were diagnosed with chronic kidney disease (CKD) and one patient with heart failure (HF). Long COVID patients ( $M = 37.76$ ,  $SD = 7.03$ ) and ME/CFS patients ( $M = 37.41$ ,  $SD = 3.51$ ) had the highest FAS scores, displaying severe fatigue. Mean FAS scores for the remaining medical conditions are displayed in Table 3. LADLS scores revealed that chronic fatigue participants were mostly independent in their daily function (scores from 4 to 8). The years after diagnosis varied greatly across the medical conditions; patients with CKD had the longest average (*Mdn* = 20 yrs.), whereas individuals with long-term COVID-19 had the shortest average (*Mdn* = 1 yr.). CFG participants, however, had relatively similar average years of fatigue RA ( $M = 2.75$ ,  $SD = 1.75$ ); OSA ( $M = 2.60$ ,  $SD = 0.89$ ); CKD ( $M = 2.33$ ,  $SD = 1.52$ ); HF (2.00); LCOVID (*Mdn* = 2), and ME/CFS (*Mdn* = 3).

#### 3.3. Psychometric self-report data and Imagery Task outcomes

Psychometric measures are presented in Table 4. PANAS revealed that CFG individuals had significantly lower positive affect scores compared with HG and higher negative affect scores than HG. FAS reported significantly higher fatigue levels for CFG individuals ( $M = 34.08$ ,  $SD = 8.93$ ) than HG ( $M = 25.89$ ,  $SD = 9.59$ ) ( $t(121) = -4.764$ ,  $p = .000$ ). In addition, the physical fatigue domain FAS score of CFG was statistically higher (*Mdn* = 20.00) than of HG (*Mdn* = 12.00), ( $U = 833.00$ ,  $p = .000$ ), as well for the mental fatigue domain scores of the FAS, the CFG (*Mdn* = 15.00) scored statistically higher than HG (*Mdn* = 11.00) ( $U = 1205.00$ ,  $p = .002$ ). Importantly, the difference in

**Table 2**  
Body characteristics in healthy group (HG) and Chronic Fatigue group (CFG).

	HG	CFG
	$N = 74$	$N = 49$
	( <i>Mdn</i> ; PCTL25; 75)	( <i>Mdn</i> ; PCTL25; 75)
Age (years)	(30.00; 21.00; 43.00)	(54.00; 41.00; 65.00)*
Ethnicity	(White British; $n = 51$ ; 69 %)	(White British; $n = 41$ ; 84 %)
Sex	(Females $n = 67$ ; 61 %)	(Females $n = 39$ ; 80 %) <sup>Δ</sup>
	( $M \pm SD$ )	( $M \pm SD$ )
NASA	3.24 ± 1.49	1.49 ± 0.82 <sup>Ⓛ</sup>
Body Mass Index (kg/ m <sup>2</sup> )	25.74 ± 6.44	29.84 ± 6.70 <sup>†</sup>
NASA: Level of physical activity; range 1–5; 1-> little or no activity; 5-> Max level of activity		
Mann-Whitney <i>U</i> statistic * (573.50) $p = 0.000$		
Pearson chi-square <sup>Δ</sup> $X^2(1) = 4.48$ $p = 0.03$ ; <sup>Ⓛ</sup> $X^2(4) = 37.55$ $p = 0.000$		
An independent t-test <sup>†</sup> $t(109) = -3.235$ $p = 0.002$		

**Table 3**  
Clinical conditions characteristics.

Condition	Total No.	Years Post Diagnosis (Mdn ; PCTL25; 75)	Fatigue (Yrs.) (Mdn ; PCTL25; PCTL75)	FAS (Mdn ; PCTL25; PCTL75)	LADLS (Mdn; PCTL25; PCTL75)
RA	4	(10.50; 7.00; 11.75)	(3.00; 1.25; 4.00)	(26.00; 23.00; 30.50)	(7.50; 6.25; 8.00)
OSA	5	(5.00 3.00  5.00)	(2.00; 2.00; 3.50)	(22.00; 20.00; 33.50)	(8.00; 7.00; 8.00)
CKD	3	(4.00  20.00  20.00)	(2.00 1.00  2.00)	(34.00  30.00  34.00)	(7.00 7.00  8.00)
HF	1	10.00	2.00	22.00	6.00
LCOVID	13	(Mdn; PCTL25; 75) (1.00; 0.65; 2.00)	(Mdn; PCTL25; 75) (2.00; 1.00; 3.50)	37.76 ± 7.03	(Mdn; PCTL25; 75) (6.00; 4.00; 7.00)
ME/CFS	17	(Mdn; PCTL25; 75) (4.00; 1.50; 8.50)	(Mdn; PCTL25; 75) (3.00; 2.00; 4.00)	37.41 ± 3.51	(Mdn; PCTL25; 75) (7.00; 5.00; 7.00)

RA -: Rheumatoid arthritis; OSA : Obstructive Sleep Apnoea; CKD-: Chronic Kidney Disease; HF: Heart Failure

LCOVID: Long Covid; ME/CFS : Myalgic encephalomyelitis or chronic fatigue syndrome

Years Post Diagnosis: Number of years after diagnosis of condition; Fatigue-: Number of years living with fatigue

FAS: Fatigue Assessment Scale; Range: ≤ 22 (no fatigue); > 22 (fatigue); >35 (severe fatigue)

LADLS-: Lawton Activities of Daily Living; Range: 0 (low function, dependent) to 8 (high function, independent)

**Table 4**  
Psychometric self-report data and Imagery Task outcomes in healthy group (HG) and in chronic fatigue group (CFG).

	HG (N = 74) (Mdn ; PCTL25; 75)	CFG (N = 49) (Mdn ; PCTL25; 75)
LADLS	-	6.20 ± 1.65
PANAS (Positive)	(29.00; 23.00; 33.25)	(21.00; 16.00; 29.00)*
PANAS (Negative)	(19.00; 16.00; 25.25)	(24.00; 19.00; 29.00) <sup>Δ</sup>
FAS (Physical)	(12.00; 9.00; 17.25)	(20.00; 17.00; 23.00) <sup>†</sup>
FAS (Mental)	(11.00; 9.00; 15.00)	(15.00; 12.00; 18.00) <sup>Φ</sup>
FAS (Total)	(M±SD) 25.89 ± 9.59	(M±SD) 34.08 ± 8.93**
Stair RPE	(11.00; 7.75; 12.00)	(13.00; 12.00; 16.00) <sup>‡</sup>

LADLS: Lawton Activities of Daily Living; Range: 0 (low function, dependent) to 8 (high function, independent)

PANAS (Positive): Positive and Negative Affect Schedule (Positive); Range:10–50;

PANAS (Negative): Positive and Negative Affect Schedule (Negative); Range:10–50;

FAS: Fatigue Assessment Scale; Range: ≤ 22 (no fatigue); >22 (fatigue); >35 (severe fatigue)

FAS (Physical): Physical fatigue; FAS(Mental): Mental fatigue

Stair RPE: Image RPE; Range:6–20; 6 (no exertion), 20 (maximal exertion)

Mann Whitney U Statistic \*(1175.50) p = 0.001; <sup>Δ</sup>(1314.00) p = 0.010; <sup>†</sup>(833.00) p = 0.000; <sup>Φ</sup>(1205.00) p = 0.002; <sup>‡</sup>(754.50) p = 0.000

Independent t-test\*\*t (121) = -4.764 p = 0.000

Icons indicate both statistical significance and test type \*, Δ, †, Φ, ‡: Mann-Whitney U test p < .001,

\*\*t: Independent t-test p < .001

FAS scores between groups was not driven by the age difference between groups. No significant correlations were found within the datasets together (CFG plus HG), and no significant correlation was found within

the healthy group. However, a small negative correlation was found within the CFG ( $\rho = -0.331$ ,  $p = 0.02$ ), showing that younger participants tended to report higher FAS scores. For the imagined stair task, a Mann-Whitney U test revealed that the predicted RPE scores of CFG ( $Mdn = 13.00$ ) were statistically higher than HG ( $Mdn = 11.00$ ) ( $U = 754.50$ ,  $p = 0.000$ ).

### 3.4. Experienced and predicted RPE

In our first hypothesis, we expected that individuals could predict the RPE of observed exercising individuals at various exertional loads. The experienced RPE and predicted RPE in HG had a significantly strong positive correlation, Spearman correlation ( $\rho(1849) = .740$ ,  $p < .001$ ). Additionally, a significant moderate correlation was found between the predicted and experienced RPE in the CFG group, Spearman correlation ( $\rho(1225) = .675$ ,  $p = .001$ ), indicating that both groups were able to predict the RPE of exercising individuals, by observation (Fig. 4).

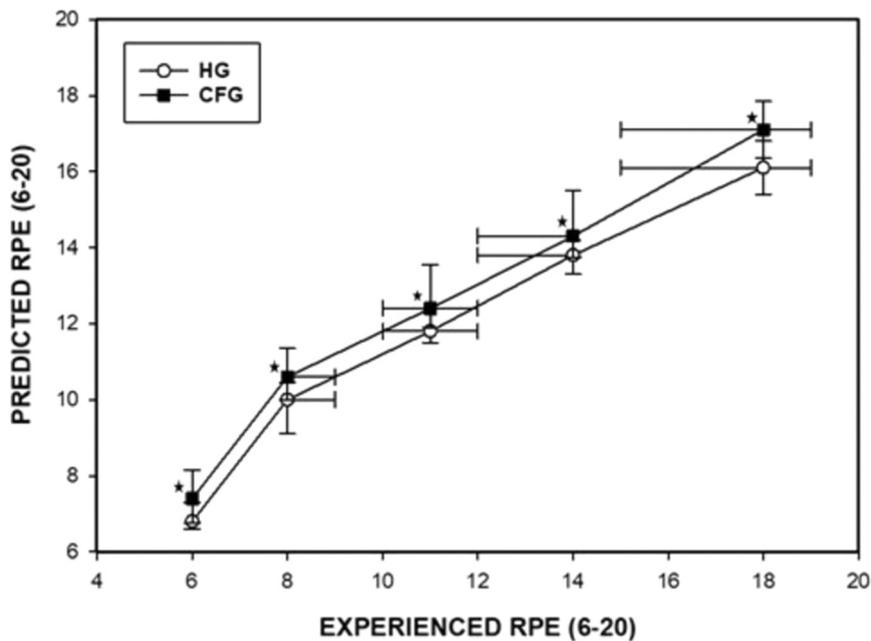
Secondly, we hypothesized that individuals with chronic fatigue would rate the RPE of the exercising individuals in the videos consistently higher than the controls, revealing a central bias towards higher effort/exertion prediction. ANCOVA analysis comparing the CFG and the HG predicted RPE values using the experienced RPE values as covariate, revealed that CFG predicted a higher RPE across all experienced RPE values than the HG ( $F:12.219$ ,  $p < 0.001$ ). Interaction of group x experienced RPE were not significant ( $F:3.035$ ,  $p = 0.082$ ), indicating that the regression slopes were similar for both groups. The group difference reflects an upward shift or higher intercept for the CFG group across all effort/exertion levels.

Investigating the deviation of the predicted RPE from the experienced RPE, in both groups, revealed there was an inverted U-shaped function when RPE bias was plotted against experienced RPE (Fig. 5); The RPE bias shifted from increasing positive towards decline with higher experienced RPEs; higher RPE ratings were connected with higher physical loads (speed) (Table 1; supplementary file). Individuals in the HG group overestimated RPE at lower loads and showed a moderate shift to underestimation at the highest loads. (Table 1; supplementary file). A similar overestimation at lower experienced RPEs was found in CFG (Fig. 5), while the curve was shifted upwards, showing that their prediction of RPE bias was fairly accurate at high experienced RPEs with minimal bias (Fig. 5).

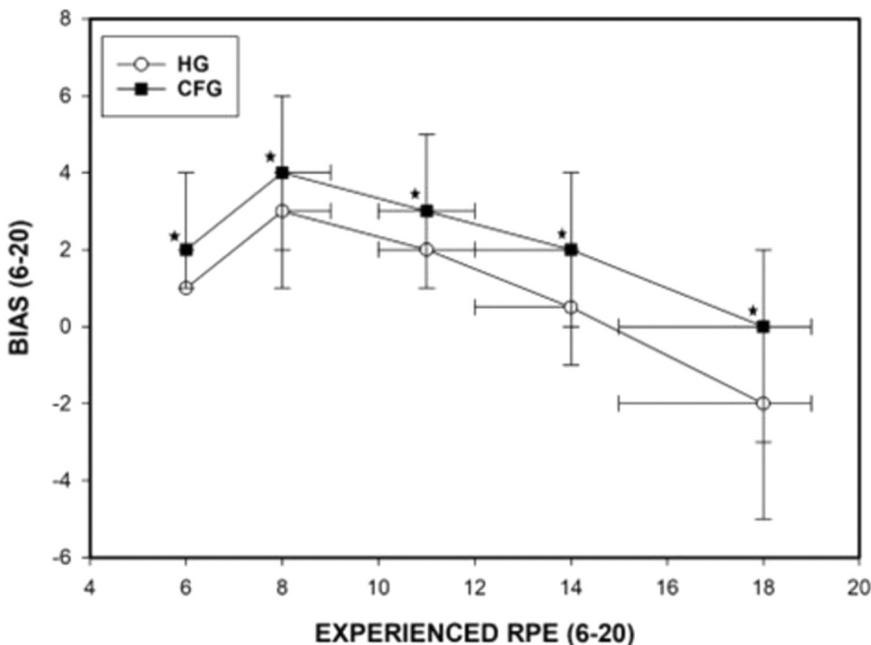
Due to the block-wise assessment of RPE prediction in our paradigm (5 randomly assigned sets of videos of individuals running at a certain speed, with 5 randomly assigned videos of exercising individuals per set), data were analysed comparing the RPE bias in set speed-blocks. Block-wise data were not normally distributed; hence, a Kruskal-Wallis H test was performed to determine the differences in the RPE bias between HG and CFG groups. Results show that there was a statistically significant difference in the median RPE bias scores between HG and CFG groups across all five speeds with the median bias score being higher at all speeds in the CFG group than the HG group ( $\chi^2(1) = 133.389$ ,  $p < 0.001$ ) (The median difference in predicted RPE between groups was approximately 1 RPE unit across speed blocks). Pairwise comparisons showed that the median bias scores of the CFG group at all five speed blocks were significantly higher than those of the HG, while the strongest effect sizes were revealed at higher speed blocks (Table 1; supplementary file).

### 3.5. Correlation analysis

In the HG, there was no significant correlation between Stair RPE and RPE bias, Spearman's  $\rho$  (1850) = .016,  $p = .502$ . However, there was a significant positive association between the Stair RPE and RPE bias in the CFG; Spearman's  $\rho$  (1225) = .174,  $p = .000$ ; higher ratings in in imagined task were associated with higher bias in RPE score for observed tasks. The correlation of RPE ratings for the imagined stair task



**Fig. 4.** Relationship between experienced and predicted RPE of healthy and chronic fatigue groups. The figure displays the median predicted Ratings of Perceived Exertion (RPE) of healthy participants (HG; open circles) and participants with chronic fatigue (CFG; filled squares) plotted against experienced RPE values of the individuals in the exercise videos. Error bars represent percentiles (25; 75). Asterisks indicate significant differences between groups at corresponding experienced RPE levels ( $p < 0.05$ ).



**Fig. 5.** RPE prediction bias across exertion levels in healthy and chronic fatigue groups. The figure illustrates the prediction bias (Predicted RPE – Experienced RPE) across levels of experienced exertion (Borg RPE 6–20) for healthy participants (HG; open circles) and individuals with chronic fatigue (CFG; filled squares). Error bars represent percentiles (25; 75). Asterisks denote statistically significant differences between groups ( $p < 0.05$ ).

with FAS scores was significant in the HG, Spearman’s  $\rho$  (1850) = .408,  $p = .000$ , as well as in the CFG, Spearman’s  $\rho$  (1225) = .422,  $p = .000$ . The physical and mental domains of the FAS showed similar strengths in positive correlation with the imagined stair task scores; for the physical domain, Spearman’s  $\rho$  (1850) = .445,  $p = .000$  in the HG group, and Spearman’s  $\rho$  (1225) = .439,  $p = .000$  was detected for the CFG group. Likewise, in the mental domain, Spearman’s  $\rho$  (1850) = .338,  $p = .000$  in the HG group and Spearman’s  $\rho$  (1225) = .329,

$p = .000$  for the CFG. Correlations within each group were small to moderate, reflecting modest inter-variable relationships in both. Table 5 summarizes the correlation analysis results.

### 3.6. Multiple linear regression

Further analysis focused on the question: what factors influenced the RPE bias in HG and CFG? We hypothesized that the bias in RPE

**Table 5**  
Correlation analysis in healthy group (HG) and chronic fatigue group (CFG).

	HG	CFG
Experienced RPE	<b>predicted RPE</b> .740*	<b>predicted RPE</b> .675*
Experienced RPE	<b>Bias</b> -.528*	<b>Bias</b> -.418*
Stair RPE	<b>Bias</b> .016	<b>Bias</b> .174*
Stair RPE	<b>FAS</b> .408*	<b>FAS</b> .422*
Stair RPE	<b>Physical</b> .445*	<b>Physical</b> .439*
Stair RPE	<b>Mental</b> .338*	<b>Mental</b> .329*

r: Spearman  $\rho$  correlation coefficient significant at  $p < 0.01$

$n = 1850$ , Observations for healthy;  $n = 1225$ , Observations for patients

Experienced RPE: RPE by person in video; Range:6–20; 6 (no exertion), 20 (maximal exertion)

Predicted RPE: RPE by person watching video; Range:6–20; 6 (no exertion), 20 (maximal exertion)

Stair RPE: Image RPE; Range:6–20; 6 (no exertion), 20 (maximal exertion)

FAS: Fatigue Assessment Scale; Range:  $\leq 22$  (no fatigue);  $>22$  (fatigue);  $>35$  (severe fatigue)

Physical: Physical fatigue; Mental: Mental fatigue

prediction (deviation between given RPE by the exercising individuals and the RPE predicted by observers) would be dependent on reported fatigue score and clinical disability of the chronic fatigue individuals, while the RPE bias of controls would be dependent on the characteristics of the observed individuals. To investigate the hypothesis, we performed multiple linear regression analysis in two blocks. Starting with the HG we used the characteristics of the observed exercising individuals in the video to explain the variance in RPE bias (first block), suggesting that healthy individuals would use cues related to age, sex, ethnicity, fitness, and speed for the prediction of the RPE of the observed individuals. In the second block, characteristics of the observing individuals were added, including physical and psychological characteristics (see Table 6) for investigating whether parameters of the observer influenced the predictions for the RPE of observed individuals in the videos. In the HG, the observed individuals' characteristics had the largest contribution for explanation of variance in RPE bias, 26 % of the variance of the RPE bias was explained,  $F(5, 1368) = 94.34, p = .000$  (block 1). Adding the observer characteristics (block 2), 29 % of the variance,  $F(14, 1359) = 39.41, p = .000$ , was explained. Therefore, adding observer characteristics improved the model only by about 3 %, revealing that the overall impact of observer characteristics, such as fatigue scores, on RPE bias was minimal in the HG. The RPE bias was mostly influenced by the characteristics of the individuals in the videos; speed ( $\beta = -.39, p < .05$ ), ethnicity ( $\beta = -.36, p < .05$ ), and age ( $\beta = .41, p < .05$ ) being the most influential. For the CFG, a contrasting result was detected, the observed characteristics (block 1) explained 16 % of the variance in the RPE bias,  $F(5, 1094) = 41.85, p = .000$ . However, by adding the observer characteristics in block 2, 30 % of the RPE bias variance,  $F(14, 1085) = 33.69, p = .000$ , was explained (see Table 7). The model improved the explanation of the variance of RPE bias by 14 % when the observer characteristics were incorporated. While this was a modest improvement in explained variance in absolute terms, the relative increase was substantially larger in CFG ( $\approx 14\%$  in CFG vs  $\approx 3\%$  in HG). The observer characteristics that had the greatest influence on the RPE bias of the CFG were fatigue scores, disability scores, and stair task RPE. The mental fatigue domain contribution ( $\beta = .37, p < .05$ ) was even higher than that of speed ( $\beta = -.29, p < .05$ ), and stair task RPE scores

**Table 6**  
Multi linear regression analysis of RPE Bias in the healthy group (HG).

	B (Constant)	Std. Error	B
Step 1			
Speed	-0.34	0.02	-.39*
Observed Sex	-0.56	1.21	-.09
Observed Ethnicity	-0.67	0.30	-.36*
Observed Age	0.09	0.04	.41*
HRperSpeed	0.09	0.10	.41
Step2			
Speed	-0.34	0.02	-.39*
Observed Sex	-0.55	1.19	-.09
Observed Ethnicity	-0.67	0.30	-.36*
Observed Age	0.09	0.04	.41*
HRperSpeed	0.09	0.10	.41
NASA Physical Activity	0.14	0.05	.07*
Observer Ethnicity	-0.10	0.07	-.04
Observer Age	0.04	0.01	.14*
Observer Sex	0.62	0.19	.11*
Observer Stair RPE	-0.07	0.03	-.06
Physical Fatigue	-0.05	0.02	-.07
Mental Fatigue	0.09	0.03	.13*
CRF	-0.02	0.04	-.02
BMI	0.02	0.02	.05

$R^2 = .26$  for Step 1,  $\Delta R^2 = .29$  for Step 2 ( $*p < .05$ )  $**p = .000$ ;  $n = 1850$   
Speed: Speed of the observed individual running in the video; from 4 km to 14 km/hr

Observed Sex: Sex of the observed individual running in the video

Observed Ethnicity: Ethnicity of the observed individual running in the video

Observed Age: Age of the observed individual running in the video

HRperSpeed: Fitness of the observed individual running in the video calculated in a regression equation.

NASA Physical Activity: Physical activity level of the observer individual looking at video

Observer Ethnicity: Ethnicity of the observer individual looking at video

Observer Age: Age of the observer individual looking at video

Observer Sex: Sex of the observer individual looking at video

Observer Stair RPE: Effort perception of the observer individual looking at video

Physical Fatigue: Physical impact of fatigue; Range:  $\leq 22$  (no fatigue);  $> 22$  (fatigue);  $> 35$  (severe fatigue)

Mental Fatigue: Mental impact of fatigue; Range:  $\leq 22$  (no fatigue);  $> 22$  (fatigue);  $> 35$  (severe fatigue)

CRF: Cardiorespiratory Fitness

BMI: Body Mass Index

had a similar contribution to the RPE bias ( $\beta = .25, p < .05$ ), as well as LADLS scores,  $\beta = .29, p < .05$ . Outcomes reveal a strong contribution of distinct observer characteristics, related to fatigue, for the prediction bias of RPE in participants with chronic fatigue, unlike seen in the control individuals.

#### 4. Discussion

This is the first study investigating the prediction of effort/exertion through observation of exercising individuals in a population experiencing chronic fatigue. For the first hypothesis, we assumed that individuals with chronic fatigue, as well as healthy controls, are capable of predicting the RPE of an observed individual exercising at different physical loads. We found a moderate to strong correlation between the RPEs predicted by the observers and the RPE reported by the exercising individuals in both groups. Indeed, our results are in agreement with previous work with healthy people, revealing similar strength in correlations between RPE values observed and reported during running and walking [41]. However, the objective of our study was to investigate and compare the prediction of observed effort/exertion between individuals with chronic fatigue and healthy controls. This allowed us to probe functional changes in the prediction of effort/exertion in chronic fatigue without the confound of afferent sensory input produced when performing a physical or cognitive task. Former work has focused on

**Table 7**  
Multi linear regression analysis of RPE Bias in the chronic fatigue group (CFG).

	B (Constant)	Std. Error	B
<b>Step 1</b>			
Speed	-0.28	0.03	-.29*
Observed Sex	-0.09	1.64	-.01
Observed Ethnicity	-0.53	0.41	-.25
Observed Age	0.06	0.06	.23
HRperSpeed	0.03	0.14	.13
<b>Step2</b>			
Speed	-0.28	0.03	-.29*
Observed Sex	-0.11	1.50	-.02
Observed Ethnicity	-0.53	0.38	-.25
Observed Age	0.06	0.05	.23
HRperSpeed	0.04	0.13	.14
NASA Physical Activity	-0.65	0.12	-.16*
Observer Ethnicity	0.72	0.16	.17*
Observer Age	0.02	0.01	.08*
Observer Sex	0.78	0.25	.10*
LADLS	0.62	0.08	.29*
Observer Stair RPE	0.27	0.04	.25*
Physical Fatigue	-0.17	0.04	-.25*
Mental Fatigue	0.28	0.04	.37*
BMI	-0.04	0.02	-.07*

$R^2 = .16$  for Step 1,  $\Delta R^2 = .30$  for Step 2 (\* $p < .05$ ) \*\* $p = .000$ ;  $n = 1225$

Speed:- Speed of the observed individual running in the video; from 4 km to 14 km/hr

Observed Sex:- Sex of the observed individual running in the video

Observed Ethnicity:- Ethnicity of the observed individual running in the video

Observed Age:- Age of the observed individual running in the video

HRperSpeed:- Fitness of the observed individual running in the video calculated in a regression equation.

NASA Physical Activity:- Physical activity level of the observer individual looking at video

Observer Ethnicity: Ethnicity of the observer individual looking at video

LADLS: Lawton Activities of Daily Living Scale; Range 0 (low function) to 8 (high function)

Observer Age:- Age of the observer individual looking at video

Observer Sex:- Sex of the observer individual looking at video

Observer Stair RPE:- Effort perception of the observer individual looking at video

Physical Fatigue:- Physical impact of fatigue; Range:  $\leq 22$  (no fatigue);  $> 22$  (fatigue);  $>35$  (severe fatigue)

Mental Fatigue:- Mental impact of fatigue; Range:  $\leq 22$  (no fatigue);  $> 22$  (fatigue);  $>35$  (severe fatigue)

BMI:- Body Mass Index

cognitive [35,66] and physical tasks [36,67], with studies consistently finding an elevation of RPE for task performance [68]. As an example, outcomes of contralateral-limb matching tasks revealed that in CFS, a greater amplitude of corollary discharge was suggested in connection with effort sensation. A higher force production in the contralateral limb in matching experiments of the ipsilateral limb performing fatiguing exercise supported a disproportionate mismatch between afferent feedback and efferent feed-forward signals [69]. However, most of the paradigms used may not completely differentiate between an elevation in prediction of effort/exertion for a task and potential changes in sensory afferent gain in connection with functional changes in chronic fatigue. Theories of effort perception in chronic fatigue emphasize the contribution of afferent feedback processing [70], corollary discharge from motor areas [71], or a combination of those as being consequential for an elevation of RPE [36,72]. In relation to the perception of effort, a differentiation into intended effort and achieved effort awareness might be useful. Lafargue & Franck [38] suggest that awareness of intended effort uses corollary discharge information upstream of M1 motor cortex areas, not including sensory feedback [73]. In addition, motor imagery and performed force production showed shared associations of event-related potentials from supplementary motor areas with target forces but not from the M1 motor area [74]. Authors suggest a crucial role of supplementary motor areas for effort generation and experience

rather than the motor areas themselves.

In our paradigm, the task does not involve anticipation of one's own action and no afferent input in relation to physical task performance; therefore, an effort prediction during observation could be the result of feed-forward signals usually performed during effort predictions for tasks, but without the influence of cost/reward evaluation for one's own action. Ludwiczak et al. [75] showed that reward size influences choice in connection with effort intention; however, perceived effort seemed more relevant for the performance of an action. An impaired reward-effort processing has also been implied in chronic fatigue [22].

In line with our first hypothesis, our results show that individuals with chronic fatigue predicted significantly higher RPE scores than the control group at all levels of RPE as reported by the exercising individuals. RPE values of the observed exercising individuals are a linear function of the levels of physical loads (speeds) and strongly influenced by their cardiovascular fitness [63]. A significant difference in the position of the regression lines (RPE given by observers versus RPE given by exercising individuals) between participant groups (CFG and HG) was observed, with an upward shift for the chronic fatigue group, in agreement with our second hypothesis, expecting elevated prediction of effort/exertion in chronic fatigue conditions. Due to the missing involvement of physical tasks in our paradigm, this result suggests an alteration in higher centre predictions for effort/exertion in participants with chronic fatigue over a lower sensory threshold or higher sensory gain [76]. The contribution of central sensitisation in CFS has been shown in numerous studies in relation to pain [77]. However, sensory amplification was reported to be associated with pain but not with fatigue in CFS patients, and the authors suggested that fatigue may operate by a different mechanism [78].

We were interested in what factors would influence the deviation of the observer-predicted RPE from that reported by the exercising individuals (the RPE bias). In our second hypothesis, we predicted that healthy controls would use visual cues connected with characteristics of the observed, like the speed of running, and facial cues related to effort [42]. We also expected cues related to learned assumptions about characteristics to play a role e.g. older people would experience higher effort than younger. Indeed, multiple linear regression models revealed that in controls, characteristics of the individuals being observed had a greater impact on the RPE bias (26 %) than their own characteristics, with personal fitness, fatigue, and imagined stair task RPE hardly contributing to the model (increased model fit by 3 %). Therefore, control subjects did not reference their own physical and mental condition when predicting the RPE of the observed individuals.

In contrast, with our third hypothesis, we expected to find that individuals with chronic fatigue would integrate factors connected with their own condition, i.e., fatigue scores, disability scores, and the stair task RPE, into the prediction of RPE of an observed individual. Indeed, using multiple linear regression models, we found that the characteristics of the observed individuals had less of a contribution to the explanation of variance of RPE bias (16 %) than they did in the healthy controls. Moreover, a large amount of the variance was explained by integrating the characteristics of the observing individuals into the model (30 %), whereby fatigue scores and stair task RPE contributed the most, next to the LADLS scores.

This finding supports the idea that the prediction of effort/exhaustion by observation is influenced by the physical and mental fatigue symptoms of individuals with chronic fatigue. This effect was seen across all investigated clinical conditions. Apart from the fatigue scores and disability scores, the imagined stair task also contributed strongly to the model. The imagined stair task used an image of a typical staircase with a typical riser height and number of steps, and focused on predicting the effort/exertion the individuals would experience if completing the task of climbing the stairs. In former work, it was shown that people's perceived affordance includes their own intrinsic capabilities [79] as well as task characteristics like the number of steps and riser height [65]. In our study, significant correlations were found

between the RPE values given in the imagined stair task with the fatigue scores of the FAS in both groups, which shows that affordance [80] includes a component of predicted capability of the self. In addition, it was shown earlier [74] that during imagery and execution of effortful tasks, specific patterns associated with variations in motor control parameters were similar in imagery and execution of effortful tasks.

Moreover, a significant correlation of the stair RPE task with RPE bias was solely found in the chronic fatigue group, pointing towards a difference in how one's own predicted capacity influenced the prediction from observation in the chronic fatigue group. People with chronic fatigue seemed to integrate some information about their own capacity into the prediction of effort during observation. Further support for this interpretation is found in the outcomes of the multiple linear regression analysis, showing that a large proportion of the variance in RPE bias can be explained by the characteristics of the observer with chronic fatigue.

A key consideration is the integration of our findings into the current theories regarding the mechanisms of chronic fatigue. While the status of inflammatory factors in our tested population was not assessed, their potentially strong influence on fatigue in certain clinical conditions is certainly beyond doubt [81]. However, often, chronic fatigue is maintained even after remission of inflammatory factors on blood levels [82], lesions and neurological alterations may persist even after reduction in inflammatory markers [21], and more complex and long-term alterations are described for ME/CFS, including various systemic alterations, i.e., autonomic system [19]. However, various clinical conditions, besides their different pathological processes, are thought to entail overlapping functional changes leading to the feeling of fatigue [83].

Theoretical models have pointed towards a higher sensitisation of the inhibition system [84]. The inhibition system is suggested to play an important role in decision-making for motor tasks and feelings of fatigue [85]. Various brain areas are suggested, and fMRI studies have supported this theoretical concept [83]. However, it is unclear whether the inhibition network would contribute directly during the process of predicting RPE during observation of other individuals performing an effortful task in our paradigm.

Our findings show that RPE bias in individuals with chronic fatigue was elevated compared with healthy controls, and the variance of RPE bias was related to symptoms of fatigue in the chronic fatigue participants. In context with the formerly mentioned studies, this could be interpreted as an influence on higher sensitivity in the inhibitory system [84], which might contribute to the altered prediction of effort/exhaustion during observations in individuals with chronic fatigue. Inference of effort/exhaustion could be a skill which adds to the principal need for representation of various stimuli for predicting consequences for another person, like empathy for painful stimuli [49]. Nonetheless, the influence of altered activation of brain areas in chronic fatigue remains speculative for our paradigm without further studies involving neuroimaging techniques (e.g. fMRI).

However, further psychological concepts may be informative for the interpretation of our findings without experimental evidence from fMRI studies using our paradigm. Metacognitive processes evaluate thoughts, observations, and beliefs about a person's own perceptual responses to the environment [86]. These can lead to negative metacognitions, being prominent in some mental health conditions like generalised anxiety disorder [87], exacerbating worry about the controllability of actions and perceptions in response to environmental cues. Particular intrusive thoughts about health threats are a consequence [88] in anxiety disorders, which may lead to avoidant behaviour [89]. In connection with chronic fatigue, the metacognitive theory of dyshomeostasis suggests that a person's interoceptive-allostatic circuitry is monitored by metacognitive processes that revise assumptions about the ability to control bodily states [29]. A chronic progressive response to interoceptive experience of poor prediction of perceived consequences of actions (physical or cognitive) would lead to low allostatic self-efficacy with concomitant feelings of fatigue and/or depression [29].

Indeed, our paradigm revealed that the RPE bias was predicted by

chronic fatigue-related parameters in the participants with chronic fatigue and not in the healthy participants. This result could be interpreted as evidence of heightened interoception resulting in negative metacognitive processes, which, in our paradigm, could lead to a 'spillover' of the negative predictions of one's own capacities towards the inferred capacity of the observed individuals in the videos. The process of inferring a level of exertion of an observed exercising individual might reveal the general tendency for a heightened negative prediction of consequences for physical actions in agreement with the theory of an involvement of metacognitive processes in chronic fatigue [29] and of a heightened sensitivity of the inhibitory system [84]. Metacognition involves processes to update observations about cognitive processes and establishes higher centre predictions for future actions and their outcomes for perception and emotions [90]. Our findings regarding a higher RPE bias in chronic fatigue during the prediction of RPE could be a sign of higher centre prediction regarding outcomes of physical action. The outcomes of our study might be particularly powerful because the paradigm does not involve performance of effortful tasks (cognitively or physically) nor the evaluation of those tasks by the performer, thereby avoiding direct afferent sensory feedback from the periphery. The contribution of altered sensory responses and gains, as well as poor motor-related gating, are suggested in chronic fatigue [77,91] and would contribute while performing physical or cognitive tasks [68]. In addition, the findings of a higher RPE bias across several underlying diseases with chronic fatigue symptoms support the metacognitive theory of a common dyshomeostasis involving the higher-order predictions through learning as a contributor to fatigue experience over a distinct pathophysiological process [26,27,29].

Future research should investigate whether the consistent increase in predicted RPE among individuals suffering from chronic fatigue could serve as a valuable focus for psychoeducational or metacognitive interventions. If biased effort predictions lead to activity avoidance or diminished behavioural engagement, implementing structured anchoring or recalibration techniques may enable individuals to form more precise expectations regarding effort/exertion. Additionally, these insights could aid clinicians by underscoring the significance of addressing effort expectations and perceptual biases throughout the rehabilitation process. Nevertheless, further intervention studies are required to determine if modifying effort predictions results in performance improvement and/or symptom alleviation.

Our study does have limitations; firstly, the sample is not completely matched in body characteristics due to differences in recruitment strategy. However, there was no significant association between fatigue scores and age within the collapsed population sample. Moreover, the contribution of age within the groups for the prediction of RPE bias variance was very small in the multiple regression models. Secondly, clinical information and classification were self-reports and therefore not based on clinical assessments performed by the research team; however, the method is shown to be valid [92]. Thirdly, the sample of participants with chronic fatigue symptoms is a convenience sample and so may exclude more severe cases (our sample showed moderate to high LADLS scores with a high level of independence) who might not be engaged in internet activities or perceive low self-efficacy for performing the online paradigm.

## 5. Conclusions

In summary, this is the first study investigating inference of effort/exertion (RPE) by observation in a clinical population with chronic fatigue. Outcomes revealed that chronic fatigue participants predicted higher levels of exertion during observation of exercising individuals than controls. Moreover, the variance of RPE bias was significantly explained by the characteristics of the observer, i.e., fatigue scores, unlike the controls, who integrated the characteristics of the observed individuals in their RPE inference. Our study suggests that higher-order predictions about effort/exertion for observed actions integrate

predictions about the self in a population with chronic fatigue in accordance with the metacognitive theory of dyshomeostasis.

### CRedit authorship contribution statement

**Dr Kubis Hans-Peter:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Conceptualization. **Paul Mullins:** Writing – review & editing, Supervision, Conceptualization. **Joe Butler:** Writing – review & editing, Conceptualization. **Yakeen Hafouda:** Investigation. **Ramakrishnan Vallilath:** Writing – original draft, Investigation, Formal analysis, Data curation.

### Funding

J.B is funded by the National Institute for Health and Care Research (NIHR) Applied Research Collaboration (ARC) North East and North Cumbria (NENC) (NIHR200173). The views expressed are those of the author(s) and not necessarily those of the NIHR the Department of Health and Social Care.

### Acknowledgments

The authors thank all the participants for taking part in the study, particularly the participants with chronic fatigue.

### Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.bbr.2026.116043](https://doi.org/10.1016/j.bbr.2026.116043).

### References

- [1] A. Sapra, P. Bhandari, *Chronic Fatigue Syndrome*, StatPearls Publishing, 2023.
- [2] L. Hernandez-Ronquillo, F. Moien-Afshari, K. Knox, J. Britz, J.F. Tellez-Zenteno, How to measure fatigue in epilepsy? The validation of three scales for clinical use, *Epilepsy Res* 95 (1–2) (Jun. 2011) 119–129, <https://doi.org/10.1016/j.epilepsyres.2011.03.010>.
- [3] G.J. Treharne, A.C. Lyons, E.D. Hale, C.E. Goodchild, D.A. Booth, G.D. Kitas, Predictors of fatigue over 1 year among people with rheumatoid arthritis, *Psychol. Health Med* 13 (4) (2008) 494–504, <https://doi.org/10.1080/13548500701796931>.
- [4] W. Chotinaiwattarakul, L.M. O'Brien, L. Fan, R.D. Chervin, Fatigue, tiredness, and lack of energy improve with treatment for OSA, *J. Clin. Sleep. Med.* 05 (03) (2009) 222–227, <https://doi.org/10.5664/jcsm.27490>.
- [5] C. Fernandez-de-las-Peñas, et al., Persistence of post-COVID symptoms in the general population two years after SARS-CoV-2 infection: a systematic review and meta-analysis, *J. Infect.* 88 (2) (Feb. 2024) 77–88, <https://doi.org/10.1016/j.jinf.2023.12.004>.
- [6] L.B. Krupp, L.A. Alveraz, N.G. LaRocca, L.C. Sheinberg, Fatigue in multiple sclerosis, *Arch. Neurol.* 45 (4) (1988) 435–437, <https://doi.org/10.1001/archneur.1988.00520280085020>.
- [7] F. Staub, J. Bogousslavsky, Fatigue after stroke: a major but neglected issue, *Cerebrovasc. Dis.* 12 (2) (2001) 75–81, <https://doi.org/10.1159/000047685>.
- [8] J.B. Cantor, et al., Fatigue after traumatic brain injury and its impact on participation and quality of life, *J. Head. Trauma Rehabil.* 23 (1) (2008) 41–51, <https://doi.org/10.1097/01.htr.0000308720.70288.af>.
- [9] M. Siciliano, L. Trojano, G. Santangelo, R. De Micco, G. Tedeschi, A. Tessitore, Fatigue in Parkinson's disease: a systematic review and meta-analysis, *Mov. Disord.* 33 (11) (2018), <https://doi.org/10.1002/mds.27461>.
- [10] T. Pendergrast, et al., Housebound versus nonhousebound patients with myalgic encephalomyelitis and chronic fatigue syndrome, *Chronic Illn.* 12 (4) (2016) 292–307, <https://doi.org/10.1177/1742395316644770>.
- [11] NICE, "Myalgic encephalomyelitis (or encephalopathy)/chronic fatigue syndrome: Diagnosis and management," 2021. [Online]. Available: (<https://www.nice.org.uk/guidance/ng206>).
- [12] J.G. Montoya, et al., Cytokine signature associated with disease severity in chronic fatigue syndrome patients, *Proc. Natl. Acad. Sci.* 114 (34) (2017), <https://doi.org/10.1073/pnas.1710519114>.
- [13] Y. Nakatomi, K. Mizuno, A. Ishii, Y. Wada, M. Tanaka, S. Tazawa, Neuroinflammation in patients with chronic fatigue syndrome/myalgic encephalomyelitis: an 11C-(R)-PK11195 PET study, *J. Nucl. Med* 55 (2014) 945–950, <https://doi.org/10.2967/jnumed.113.131045>.
- [14] T. Nelson, L. Zhang, H. Guo, L. Nacul, X. Song, Brainstem abnormalities in myalgic encephalomyelitis/Chronic fatigue syndrome: a scoping review and evaluation of magnetic resonance imaging findings, *Front Neurol.* 12 (2021), <https://doi.org/10.3389/fneur.2021.769511>.
- [15] Z.Y. Shan, et al., Brain function characteristics of chronic fatigue syndrome: a task fMRI study, *Neuroimage Clin.* 19 (2018) 279–286, <https://doi.org/10.1016/j.nicl.2018.04.025>.
- [16] S. Myhill, N.E. Booth, J. McLaren-Howard, Chronic fatigue syndrome and mitochondrial dysfunction, *Int. J. Clin. Exp. Med.* 2 (2009) 1–16.
- [17] F. Hoel, A. Hoel, I.K. Pettersen, I.G. Rekeland, K. Risa, K. Alme, A map of metabolic phenotypes in patients with myalgic encephalomyelitis/chronic fatigue syndrome, *JCI Insight* 6 (2021), <https://doi.org/10.1172/jci.insight.149217>.
- [18] C.W. Armstrong, N.R. McGregor, D.P. Lewis, H.L. Butt, P.R. Gooley, Metabolic profiling reveals anomalous energy metabolism and oxidative stress pathways in chronic fatigue syndrome patients, *Metabolomics* 11 (6) (2015) 1626–1639, <https://doi.org/10.1007/s11306-015-0816-5>.
- [19] J.L. Newton, O. Okonkwo, K. Sutcliffe, A. Seth, J. Shin, D.E.J. Jones, Symptoms of autonomic dysfunction in chronic fatigue syndrome, *QJM Int. J. Med.* 100 (8) (Aug. 2007) 519–526, <https://doi.org/10.1093/QJMED/HCM057>.
- [20] L. Martínez-Martínez, T. Mora, A. Vargas, M. Fuentes-Iniestra, M. Martínez-Lavín, Sympathetic nervous system dysfunction in Fibromyalgia, chronic fatigue syndrome, irritable bowel syndrome, and interstitial cystitis, *JCR J. Clin. Rheumatol.* 20 (3) (2014) 146–150, <https://doi.org/10.1097/rhu.000000000000089>.
- [21] A. Chaudhuri, P.O. Behan, Fatigue in neurological disorders, *Lancet* 363 (9413) (2004) 978–988, [https://doi.org/10.1016/S0140-6736\(04\)15794-2](https://doi.org/10.1016/S0140-6736(04)15794-2).
- [22] E. Dobryakova, J. DeLuca, H.M. Genova, G.R. Wylie, Neural correlates of cognitive fatigue: cortico-striatal circuitry and effort–reward imbalance, *J. Int. Neuropsychol. Soc.* 19 (8) (2013) 849–853, <https://doi.org/10.1017/s1355617713000684>.
- [23] B. Walitt, et al., Deep phenotyping of post-infectious myalgic encephalomyelitis/chronic fatigue syndrome, *Nat. Commun.* 15 (2024) 907, <https://doi.org/10.1038/s41467-024-45107-3>.
- [24] M. Tanaka, Y. Watanabe, A new hypothesis of chronic fatigue syndrome: Co-conditioning theory, *Med Hypotheses* 75 (2) (Aug. 2010) 244–249, <https://doi.org/10.1016/j.mehy.2010.02.032>.
- [25] A. Ishii, M. Tanaka, M. Iwamae, C. Kim, E. Yamano, Y. Watanabe, Fatigue sensation induced by the sounds associated with mental fatigue and its related neural activities: revealed by magnetoencephalography, *Behav. Brain Funct.* 9 (1) (Jun. 2013) 1–10, <https://doi.org/10.1186/1744-9081-9-24/TABLES/1>.
- [26] M. Tanaka, A. Ishii, Y. Watanabe, Neural correlates of central inhibition during physical fatigue, *PLoS One* 8 (7) (2013) e70949, <https://doi.org/10.1371/JOURNAL.PONE.0070949>.
- [27] B. Lenaert, R. Jansen, C.M. van Heugten, You make me tired: an experimental test of the role of interpersonal operant conditioning in fatigue, *Behav. Res. Ther.* 103 (2018) 12–17, <https://doi.org/10.1016/j.brat.2018.01.006>.
- [28] K. Wada, et al., Effort-reward imbalance and social support are associated with chronic fatigue among medical residents in Japan, *Int. Arch. Occup. Environ. Health* 81 (3) (Jan. 2008) 331–336, <https://doi.org/10.1007/S00420-007-0217-9/FIGURES/2>.
- [29] K.E. Stephan, et al., Allostatic self-efficacy: a metacognitive theory of dyshomeostasis-induced fatigue and depression, *Front Hum. Neurosci.* 10 (2016), <https://doi.org/10.3389/fnhum.2016.00550>.
- [30] A. Greenhouse-Tucknott, et al., Toward the unity of pathological and exertional fatigue: a predictive processing model, *Cogn. Affect Behav. Neurosci.* 22 (2) (2022) 215–228, <https://doi.org/10.3758/s13415-021-00958-x>.
- [31] P. Cisek, Cortical mechanisms of action selection: the affordance competition hypothesis, *Philos. Trans. R. Soc. B Biol. Sci.* 362 (1485) (2007) 1585–1599, <https://doi.org/10.1098/rstb.2007.2054>.
- [32] P. Cisek, J.F. Kalaska, Neural mechanisms for interacting with a world full of action choices, *Annu Rev. Neurosci.* 33 (1) (2010) 269–298, <https://doi.org/10.1146/annurev.neuro.051508.135409>.
- [33] C.S. Carver, T.L. White, Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: the BIS/BAS scales, *J. Pers. Soc. Psychol.* 67 (2) (1994) 319–333, <https://doi.org/10.1037/0022-3514.67.2.319>.
- [34] L. Schmidt, M. Lebreton, M.L. Cléry-Melin, J. Daunizeau, M. Pessiglione, Neural mechanisms underlying motivation of mental versus physical effort, *PLoS Biol.* 10 (2) (Feb. 2012), <https://doi.org/10.1371/JOURNAL.PBIO.1001266>.
- [35] A. Wearden, L. Appleby, Cognitive performance and complaints of cognitive impairment in chronic fatigue syndrome (CFS), *Psychol. Med* 27 (1) (1997) 81–90, <https://doi.org/10.1017/s0033291796004035>.
- [36] E.E. Barhorst, W.E. Andrae, T.J. Rayne, M.J. Falvo, D.B. Cook, J.B. Lindheimer, Elevated perceived exertion in people with myalgic encephalomyelitis/Chronic fatigue syndrome and Fibromyalgia: a meta-analysis, *Med. Sci. Sports Exerc* 52 (12) (2020) 2615–2627, <https://doi.org/10.1249/mss.0000000000002421>.
- [37] D.B. Cook, et al., Cardiopulmonary, metabolic, and perceptual responses during exercise in myalgic encephalomyelitis/Chronic fatigue syndrome (Me/Cfs): a multi-site clinical assessment of me/Cfs (Mcam) sub-study, *PLoS One* 17 (3) (2022) e0265315, <https://doi.org/10.1371/journal.pone.0265315>.
- [38] G. Lafargue, N. Franck, Effort awareness and sense of volition in schizophrenia, *Conscious Cogn.* 18 (1) (2009) 277–289, <https://doi.org/10.1016/j.concog.2008.05.004>.
- [39] S.C. Gandevia, The perception of motor commands or effort during muscular paralysis, *Brain* 105 (Pt 1) (1982) 151–159, <https://doi.org/10.1093/BRAIN/105.1.151>.
- [40] S.C. Gandevia, D.I. McCloskey, Interpretation of perceived motor commands by reference to afferent signals, *J. Physiol.* 283 (1) (1978) 193–199, <https://doi.org/10.1113/jphysiol.1978.sp012515>.

- [41] M. Gallagher, R.J. Robertson, F.L. Goss, I. Kane, E.F. Nagle, and K.A. Tessmer, "Exertional Observation in Adults Performing Intermittent Treadmill Walking and Running," *Int J Exerc Sci*, vol. 10, no. 8, pp. 1130–1144, 2017, [Online]. Available: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5786197/>.
- [42] W.J. Rejeski, C.A. Lowe, Nonverbal expression of effort as causally relevant information, *Pers. Soc. Psychol. Bull.* 6 (3) (1980) 436–440, <https://doi.org/10.1177/014616728063017>.
- [43] H.M. De Morree, S.M. Marcora, The face of effort: frowning muscle activity reflects effort during a physical task, *Biol. Psychol.* 85 (3) (2010) 377–382, <https://doi.org/10.1016/j.biopsycho.2010.08.009>.
- [44] F. Pavani, C. Spence, J. Driver, Visual capture of touch: out-of-the-Body experiences with rubber gloves, *Psychol. Sci.* 11 (5) (2000) 353–359, <https://doi.org/10.1111/1467-9280.00270>.
- [45] H.H. Ehrsson, C. Spence, R.E. Passingham, That's my hand! Activity in Premotor cortex reflects feeling of ownership of a limb, *Science* (1979) 305 (5685) (2004) 875–877, <https://doi.org/10.1126/science.1097011>.
- [46] M. Iacoboni, I. Molnar-Szakacs, V. Gallese, G. Buccino, J.C. Mazziotta, G. Rizzolatti, Grasping the intentions of others with one's own mirror Neuron system, *PLoS Biol.* 3 (3) (2005) e79, <https://doi.org/10.1371/journal.pbio.0030079>.
- [47] L.M. Oberman, J.A. Pineda, V.S. Ramachandran, The human mirror Neuron system: a link between action observation and social skills, *Soc. Cogn. Affect Neurosci.* 2 (1) (2007) 62–66, <https://doi.org/10.1093/scan/nsl022>.
- [48] D. Jiang, M.G. Edwards, P. Mullins, N. Callow, The neural substrates for the different modalities of movement imagery, *Brain Cogn.* 97 (Jul. 2015) 22–31, <https://doi.org/10.1016/J.BANDC.2015.04.005>.
- [49] T. Singer, B. Seymour, J. O'Doherty, H. Kaube, R.J. Dolan, C.D. Frith, Empathy for pain involves the affective but not sensory components of pain, *Science* (1979) 303 (5661) (2004) 1157–1162, <https://doi.org/10.1126/science.1093535>.
- [50] G. Borg, Borg's Perceived Exertion and Pain Scales, *Human Kinetics Publishers*, 1998.
- [51] S.B. Hulley, S.R. Cummings, W.S. Browner, D.G. Grady, T.B. Newman, *Des. Clin. Res.* (2013).
- [52] E. Erdfelder, F. FAul, A. Buchner, A.G. Lang, Statistical power analyses using G\*Power 3.1: tests for correlation and regression analyses, *Behav. Res Methods* 41 (4) (2009) 1149–1160, <https://doi.org/10.3758/BRM.41.4.1149/METRICS>.
- [53] D. Watson, L.A. Clark, A. Tellegen, Development and validation of brief measures of positive and negative affect: the PANAS scales, *J. Pers. Soc. Psychol.* 54 (6) (1988) 1063–1070, <https://doi.org/10.1037/0022-3514.54.6.1063>.
- [54] J.R. Crawford, J.D. Henry, The positive and negative affect schedule (PANAS): construct validity, measurement properties and normative data in a large non-clinical sample, *Br. J. Clin. Psychol.* 43 (Pt 3) (Sep. 2004) 245–265, <https://doi.org/10.11348/0144665031752934>.
- [55] H.J. Michielsen, J. De Vries, G.L. Van Heck, Psychometric qualities of a brief self-rated fatigue measure, *J. Psychosom. Res* 54 (4) (2003) 345–352, [https://doi.org/10.1016/S0022-3999\(02\)00392-6](https://doi.org/10.1016/S0022-3999(02)00392-6).
- [56] J. De Vries, H. Michielsen, G.L. Van Heck, M. Drent, Measuring fatigue in sarcoidosis: the Fatigue Assessment Scale (FAS), *Br. J. Health Psychol.* 9 (Pt 3) (2004) 279–291, <https://doi.org/10.1348/1359107041557048>.
- [57] S. Lookzadeh, et al., Evaluation of the reliability and validity of the Persian version of the fatigue assessment scale in Iranian sarcoidosis patients, *Open Access Maced. J. Med Sci.* 6 (7) (2018) 1310–1314, <https://doi.org/10.3889/oamjms.2018.242>.
- [58] I. Vergara, A. Bilbao, M. Orive, S. Garcia-Gutierrez, G. Navarro, J. Quintana, Validation of the Spanish version of the Lawton IADL scale for its application in elderly people, *Health Qual. Life Outcomes* 10 (1) (2012) 130, <https://doi.org/10.1186/1477-7525-10-130>.
- [59] M.P. Lawton, E.M. Brody, Assessment of older people: Self-maintaining and instrumental activities of daily living, *Gerontologist* 9 (3) (1969) 179–186, <https://doi.org/10.1093/geront/9.3.part.179>.
- [60] R. Jurca, et al., Assessing cardiorespiratory fitness without performing exercise testing, *Am. J. Prev. Med* 29 (3) (2005) 185–193, <https://doi.org/10.1016/j.amepre.2005.06.004>.
- [61] A.S. Jackson, S.N. Blair, M.T. Mahar, L.T. Wier, R.M. Ross, J.E. Stuteville, Prediction of functional aerobic capacity without exercise testing, *Med Sci. Sports Exerc* 22 (6) (1990) 863, <https://doi.org/10.1249/00005768-199012000-00021>.
- [62] K. Mitchell, M. Graff, C. Hedt, J. Simmons, Reliability and validity of a smartphone pulse rate application for the assessment of resting and elevated pulse rate, *Physiother. Theory Pr.* 32 (6) (2016) 494–499, <https://doi.org/10.1080/09593985.2016.1203046>.
- [63] G.A. Borg, Psychophysical bases of perceived exertion, *Med. Sci. Sports Exerc* 14 (5) (1982) 377, <https://doi.org/10.1249/00005768-198205000-00012>.
- [64] N. Williams, The borg rating of perceived exertion (RPE) scale, *Occup. Med (Chic. Ill.)* 67 (5) (2017) 404–405, <https://doi.org/10.1093/occmed/kqx063>.
- [65] W.H. Warren, Perceiving affordances: visual guidance of stair climbing, *J. Exp. Psychol. Hum. Percept. Perform.* 10 (5) (1984) 683–703, <https://doi.org/10.1037/0096-1523.10.5.683>.
- [66] M.L. Joustra, C.A. Hartman, S.J.L. Bakker, J.G.M. Rosmalen, Cognitive task performance and subjective cognitive symptoms in individuals with chronic fatigue syndrome or fibromyalgia: a cross-sectional analysis of the lifelines cohort study, *Psychosom. Med* 84 (9) (Nov. 2022) 1087–1095, <https://doi.org/10.1097/PSY.0000000000001117>.
- [67] J.H.M.M. Vercoulen, et al., Physical activity in chronic fatigue syndrome: assessment and its role in fatigue, *J. Psychiatr. Res* 31 (6) (1997) 661–673, [https://doi.org/10.1016/S0022-3956\(97\)00039-3](https://doi.org/10.1016/S0022-3956(97)00039-3).
- [68] J.B. Lindheimer, E.E. Barhorst, W.E. Andrae, T.J. Rayne, M.J. Falvo, D.B. Cook, Perceived exertion is elevated in chronic fatigue syndrome and Fibromyalgia: A meta-analysis of case-control studies, *Med Sci. Sports Exerc* 52 (7S) (2020) 497, <https://doi.org/10.1249/01.mss.00000679540.68177.0f>.
- [69] K.E. Wallman, P. Sacco, Sense of effort during a fatiguing exercise protocol in chronic fatigue syndrome, *Res. Sports Med.* 15 (1) (Jan. 2007) 47–59, <https://doi.org/10.1080/15438620601184331>.
- [70] B.J. Noble, R.J. Robertson, *Perceived Exertion, Human Kinetics Champaign, Champaign, IL*, 1996.
- [71] S. Marcora, Perception of effort during exercise is independent of afferent feedback from skeletal muscles, heart, and lungs, *J. Appl. Physiol.* 106 (6) (2009) 2060–2062, <https://doi.org/10.1152/jappphysiol.90378.2008>.
- [72] M. Amann, G.M. Blain, L.T. Proctor, J.J. Sebranek, D.F. Pegelow, J.A. Dempsey, Group III and IV muscle afferents contribute to ventilatory and cardiovascular response to rhythmic exercise in humans, *J. Appl. Physiol.* 109 (4) (Oct. 2010) 966–976, <https://doi.org/10.1152/JAPPLPHYSIOL.00462.2010/ASSET/IMAGES/LARGE/ZDG0101092330005.JPG>.
- [73] R.G. Carson, S. Riek, N. Shahbazzpour, Central and peripheral mediation of human force sensation following eccentric or concentric contractions, *J. Physiol.* 539 (3) (2002) 913–925, <https://doi.org/10.1113/JPHYSIOL.2001.013385>.
- [74] D.H. Romero, M.G. Lacourse, K.E. Lawrence, S. Schandler, and M.J. Cohen, "Event-related potentials as a function of movement parameter variations during motor imagery and isometric action," *Behavioural Brain Research*, vol. 117, 2000, Accessed: Feb. 16, 2025. [Online]. Available: [www.elsevier.com/locate/bsbr](http://www.elsevier.com/locate/bsbr).
- [75] A. Ludwiczak, M. Osman, M. Jahanshahi, Redefining the relationship between effort and reward: Choice-execution model of effort-based decisions, *Behav. Brain Res.* 383 (2020), <https://doi.org/10.1016/J.BBR.2020.112474>.
- [76] J. Nijs, C. Paul van Wilgen, J. Van Oostervijk, M. van Ittersum, M. Meeus, How to explain central sensitization to patients with 'unexplained' chronic musculoskeletal pain: practice guidelines, *Man Ther.* 16 (5) (Oct. 2011) 413–418, <https://doi.org/10.1016/J.MATH.2011.04.005>.
- [77] J. Nijs, et al., In the mind or in the brain? Scientific evidence for central sensitisation in chronic fatigue syndrome, *Eur. J. Clin. Invest* 42 (2) (2012) 203–212, <https://doi.org/10.1111/J.1365-2362.2011.02575.X>.
- [78] M.E. Geisser, C.S. Donnell, F. Petzke, R.H. Gracely, D.J. Clauw, D.A. Williams, Comorbid somatic symptoms and functional status in patients with fibromyalgia and chronic fatigue syndrome: sensory amplification as a common mechanism, *Psychosomatics* 49 (3) (2008) 235–242, <https://doi.org/10.1176/APPI.PSY.49.3.235>.
- [79] L.S. Mark, Eyeheight-scaled information about affordances: a study of sitting and stair climbing, *J. Exp. Psychol. Hum. Percept. Perform.* 13 (3) (1987) 361–370, <https://doi.org/10.1037//0096-1523.13.3.361>.
- [80] J. Gibson, *Perceiving, Acting, and Knowing. Toward an Ecological Psychology*, in: R. Shaw, J. Bransford (Eds.), *The Theory of Affordances*, Lawrence Erlbaum Associates, Hillsdale: NJ, 1977, pp. 67–82.
- [81] G. Chmielewski, M.S. Majewski, J. Kuna, M. Mikiewicz, M. Krajewska-Włodarczyk, Fatigue in inflammatory joint diseases, *Int J. Mol. Sci.* 24 (15) (2023) 12040, <https://doi.org/10.3390/ijms241512040>.
- [82] D. Van Hoogmoed, J. Franssen, H. Repping-Wuts, L. Spee, G. Bleijenberg, P. Van Riel, The effect of anti-TNF- $\alpha$  vs. DMARDs on fatigue in rheumatoid arthritis patients, *Scand. J. Rheuma* 42 (1) (2013) 15–19, <https://doi.org/10.3109/03009742.2012.709878>.
- [83] G.R. Wylie, B. Yao, H.M. Genova, M.H. Chen, J. DeLuca, Using functional connectivity changes associated with cognitive fatigue to delineate a fatigue network, *Sci. Rep.* 10 (1) (2020), <https://doi.org/10.1038/s41598-020-78768-3>.
- [84] S. Braem, W. Duthoo, W. Notebaert, Punishment sensitivity predicts the impact of punishment on cognitive control, *PLoS One* 8 (9) (2013) e74106, <https://doi.org/10.1371/journal.pone.0074106>.
- [85] M. Bossola, L. Angioletti, E. Di Stasio, C. Vulpio, D. De Filippis, M. Balconi, Reward (BIS/BAS) mechanisms and fatigue in patients on chronic hemodialysis, *Psychol. Health Med* 25 (6) (2019) 710–718, <https://doi.org/10.1080/13548506.2019.1653477>.
- [86] A. Wells, S. Cartwright-Hatton, A short form of the metacognitions questionnaire: properties of the MCQ-30, *Behav. Res. Ther.* 42 (4) (2004) 385–396, [https://doi.org/10.1016/S0005-7967\(03\)00147-5](https://doi.org/10.1016/S0005-7967(03)00147-5).
- [87] A. Wells, K. Carter, Further tests of a cognitive model of generalized anxiety disorder: Metacognitions and worry in GAD, panic disorder, social phobia, depression, and nonpatients, *Behav. Ther.* 32 (1) (2001) 85–102, [https://doi.org/10.1016/S0005-7894\(01\)80045-9](https://doi.org/10.1016/S0005-7894(01)80045-9).
- [88] A. Wells, *A practice manual and conceptual guide. Cognitive therapy of anxiety disorders*, John Wiley & Sons, 1997.
- [89] S.G. Hofmann, A.C. Hay, Rethinking avoidance: Toward a balanced approach to avoidance in treating anxiety disorders, *J. Anxiety Disord.* 55 (2018) 14–21, <https://doi.org/10.1016/j.janxdis.2018.03.004>.
- [90] J.E. Szczepanik, H. Brycz, P. Kleka, A. Fanslau, C.A. Zarate, A.C. Nugent, Metacognition and emotion – How accurate perception of own biases relates to positive feelings and hedonic capacity, *Conscious Cogn.* 82 (2020) 102936, <https://doi.org/10.1016/j.concog.2020.102936>.
- [91] A. Kuppaswamy, The neurobiology of pathological fatigue: new models, new questions, *Neuroscientist* 28 (3) (2022) 238–253, [https://doi.org/10.1177/1073858420985447/ASSET/IMAGES/LARGE/10.1177\\_1073858420985447-FIG4.JPG](https://doi.org/10.1177/1073858420985447/ASSET/IMAGES/LARGE/10.1177_1073858420985447-FIG4.JPG).
- [92] R. Kehoe, S.Y. Wu, M.C. Leske, L.T. Chylack, Comparing self-reported and physician-reported medical history, *Am. J. Epidemiol.* 139 (8) (1994) 813–818, <https://doi.org/10.1093/OXFORDJOURNALS.AJE.A117078>.