Prolonged cognitive activity increases perception of fatigue but does not influence perception of effort, affective valence or performance during subsequent isometric endurance exercise.

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RUNNING HEAD:

Mental Fatigue and Muscular Endurance Performance

Abstract

Performance of a cognitively demanding task has previously been reported to impair subsequent physical endurance performance, an effect attributed to sensory processes influencing the perceived effort required to maintain performance. However, there is uncertainty regarding the robustness of these performance effects and their putative mechanisms. The present study examined two hypotheses: (1) that prior cognitive activity impairs subsequent physical endurance performance and (2) that the perception of fatigue arising from sustained cognitive performance is associated with the level of effort and affective valence reported during a subsequent physical endurance task. Eighteen participants completed a high (HIGH; a modified version of the Stroop task) and low (LOW; watching a documentary) cognitively demanding task before performing an exhaustive, submaximal (20% maximal voluntary contraction, MVC) isometric contraction of the right knee extensor muscles. The perception of fatigue was elevated and cognitive task accuracy reduced in the HIGH condition. However, physical endurance performance, perception of effort and affective valence reported during the physical endurance task were not affected. In the HIGH condition, the perception of effort and affect were related to endurance time, while significant correlations were found between perceptions of fatigue and both perceived effort and affective valence when assessed across both conditions. The findings indicate that performing a demanding cognitive task does not impair subsequent physical endurance performance nor influence perceived effort and affective valence during a submaximal isometric contraction performed to task failure. The observed relationships offer some support to the idea that fatigue perception may influence affective valence and effort perception.

Key words: Mental fatigue, cognitive fatigue, exercise tolerance, exhaustion.

1. Introduction

Fatigue is a complex and multidimensional phenomenon. Fatigue may emerge in health, following extended exertion (Enoka & Duchateau, 2016), or in disease, presenting as a primary/secondary symptom or comorbidity in many neurological conditions (Penner & Paul, 2017). Fatigue may be distinguished based on its domain of origin, with modifiers often incorporated to describe the transient symptoms of fatigue induced from engagement in prolonged and demanding cognitive activity (i.e. cognitive or mental fatigue; here, we do not differentiate between terms and will use mental fatigue consistently throughout; c.f. Ackerman & Kanfer, 2009) versus the performance of physical tasks (i.e. physical fatigue). Mental fatigue is described as a psychophysiological state, which may be characterised by an increased aversion to exertion, perceptual changes including elevated perceptions of effort, tiredness or exhaustion, and accompanied by a decrease in cognitive performance (Boksem & Tops, 2008). Physical fatigue is typically associated with a decline in the physiological capacity of a muscle to produce or sustain force and accompanied by an increased perception of the effort required to exert force (Enoka & Stuart, 1992). In both domains, fatigue may therefore be characterised across two independent, but interactive attributes: a subjective perceptual component and/or a decline in some objective performance criterion (Enoka & Duchateau, 2016; Kluger et al., 2013).

Deleterious effects of prolonged cognitive activity on cognitive performance, and consequent development of (mental) fatigue, have been well documented (e.g. Boksem et al., 2006; Gergelyfi et al., 2015; Hopstaken et al., 2015). Studies have also indicated that this negative effect may transcend domains, with performance of demanding cognitive tasks impairing subsequent performance of physical tasks (Pageaux & Lepers, 2018; Van Cutsem, Marcora, et al., 2017). Two recently published meta-analyses concluded that prior cognitive exertion incurs a small-to-moderate effect on several indices of physical performance (Brown et al., 2020; Giboin & Wolff, 2019). Of note, there was evidence for an impairment of physical endurance performance. Experimental evidence indicates that this effect is independent of overt changes to neuromuscular function (Pageaux et al., 2013; also see Pageaux et al., 2015; Rozand et al., 2014). However, several studies have subsequently failed to confirm the negative effects of a cognitively demanding task on physical performance (Holgado et al., 2020;

Martin et al., 2016; Silva-Cavalcante et al., 2018; Van Cutsem, De Pauw, et al., 2017). For example, a replication study from Holgado et al. (2020) failed to support research findings reported in the seminal work of Marcora et al. (2009). Two other meta-analyses have reported that the deleterious effect of prior cognitive activity on physical endurance performance may be marginal, raising concerns regarding the veracity of the effect and putative causal mechanisms (Holgado, Sanabria, et al., 2020; McMorris et al., 2018). This discrepancy may be attributable to various methodological differences within the meta-analyses, for example, adopted inclusion criteria such as the duration of the cognitive intervention. This discrepancy may be attributable to various methodological differences within the meta-analyses, for example, adopted inclusion criteria such as the duration of the cognitive intervention (that is, cognitive tasks of >30 minutes have defined the study of "mental fatigue" in the sport and exercise literature [see Holgado, Sanabria, et al., 2020; Van Cutsem, Marcora, et al., 2017] whereas shorter duration tasks are typically used in the examination of the "ego depletion" phenomena within cognitive psychology [Brown et al., 2020], with this concept separation potentially serving only to exacerbate division between interested research fields [Pattyn et al., 2018]). Divergent conclusions drawn from the effect of prior cognitive activity on subsequent physical performance by recent meta-analyses (Brown et al., 2020; Giboin & Wolff, 2019; Holgado, Sanabria, et al., 2020; McMorris et al., 2018) may be attributable, at least in part, to this portioning. What is clear, is that further evaluation of the mental fatigue – physical performance relationship is required, as is the need for a re-examination of the effects reported within the literature. Synthesis of effects has indicated that isolated, single-muscle endurance tasks may be most sensitive to the negative effects of prior cognitive activity due to higher attentional demands involved in its motor control (Giboin & Wolff, 2019). However, there is a limited number of studies examining this effect. Pageaux et al. (2013) reported that 90 mins of sustained cognitive activity caused participants to experience elevated perception of effort during a sustained, submaximal contraction of the knee extensors, and a 13% reduction in the time participants were able to tolerate the contraction. It is our primary intention to re-examine this effect in order to further understand its deleterious impact on subsequent endurance performance.

Putative effects on physical endurance performance following cognitive exertion suggest that performance between domains may connected by some shared underlying mechanisms. Review of the current neurophysiological and neuroimaging evidence has indicated the both physical and cognitive exertion may alter activity within a domain-general, motivation system (Müller & Apps, 2019). This system is believed to monitor the declining gain in the neuronal activity of task-relevant systems incurred through repetitive stimulation, deciding whether to exert further effortful control based on outcome utility (Müller & Apps, 2019). Similarly, phenomenological and behavioural reports postulate prior cognitive activity may impair performance by altering processes involved in how effortful subsequent physical tasks are perceieved to be (Pageaux & Lepers, 2016) or more general motivational functions (Martin et al., 2018). However, we and others have argued that attribution of the perception of effort as the principal mechanism for these observed effects may be due, at least in part, to an almost exclusive reliance on the assessment of perceived effort in the description of the regulation of behavioural performance (Greenhouse-Tucknott et al., 2020; Venhorst et al., 2017). Other psychological processes, including affective valence, have been shown to be an important component of self-regulation during physical endurance performance (Hartman et al., 2019; Jones et al., 2015) and may help further understand the deleterious effect of a prior cognitively demanding task. For instance, Ávila-Gandía et al.(2020) recently demonstrated that greater load on executive processes during prolonged physical performance was accompanied by increased arousal and less positive affective valence but had little effect on perception of effort during the physical task. In addition, the perception of effort has often been erroneously conflated, and used synonymously with the perception of fatigue (Borg, 1986; Halperin & Emanuel, 2020). The perception of fatigue may be disassociated from the perception of effort during and after physical performance (McAuley et al., 1999; Micklewright et al., 2017). As such, current understanding of the precise role of both affective valence and fatigue perception, whether induced by a cognitive or physical demanding task, in behaviour regulation is limited. We recently demonstrated that prior physical exhaustive exercise in the upper body impaired individual's ability to sustain a subsequent contraction in the lower limbs, and was attributed to interactive relationships between affective valence, effort and fatigue perceptions during the subsequent physical task (Greenhouse-Tucknott et al., 2020). Specifically, the perception of fatigue was not associated with performance directly, but was implicated in the indirect regulation of physical endurance performance through modulation of regulatory perceptual (i.e. effort) and affective processes (Greenhouse-Tucknott et al., 2020). Similar relationships between the perception of fatigue and perceived effort have been suggested following prior cognitive activity (Harris & Bray, 2019), but this effect requires further examination.

The aims of the present study were two-fold: (1) To ascertain whether a prolonged, demanding cognitive task impairs both cognitive and physical performances (objective measures); (2) To examine the effect of perceived fatigue on perceived effort and affect during the subsequent physical task. It was hypothesised that the prior cognitive task would reduce accuracy and increase response time of a modified Stroop task, impair subsequent physical endurance performance and modulate perceptual and affective responses during the physical task.

2. Method

2.1. Participants

Using G*Power (Faul et al., 2007), a priori sample size estimations were based on the main dependent variables of interest ($\alpha = 0.05$; $1-\beta = 0.80$), which were the effect of the cognitive task on the subsequent physical endurance performance and the relationship between the perception of fatigue and the perception of effort. For the former, based on the effect size (Cohen's d_{av} of 1.49) reported by Pageaux et al (2013) for the same physical task (i.e. sustained isometric contraction of the at 20% of Maximal Voluntary Contraction; MVC), a minimum sample of 7 participants was estimated. For the latter, based on the effect size (r_{rm}=0.60) observed in our previous study (Greenhouse-Tucknott et al., 2020) a minimum sample of 17 participants was estimated. Eighteen healthy participants (7 female; $M \pm SD$, 22 ± 2 years, 1.72 ± 0.09 m, 72.2 ± 14.5 kg) volunteered to take part in the present study. All participants were medication free and had no history of cardiovascular, neurological or musculoskeletal disorders. Participants were instructed to refrain from caffeine, alcohol and strenuous exercise for 24 hours prior to each session. The study was approved by the University's Research Ethics Committee and conducted based on the principles of the *Declaration of Helsinki,* except prior registration of the study in a database.

2.2. Experimental Procedures

Participants were naïve to the true aims of the study and were led to believe that the study was designed to assess the effect of two different cognitive tasks on endurance performance during a subsequent physical task. Participants visited the laboratory on three occasions, each performed at the same time of day (±1 hr) and separated by a minimum of 48 hrs. A schematic of the research design is presenting in Figure 1. During the first preliminary session, participants were familiarised with all measures and experimental procedures. The second and third visits represented the experimental trials. Upon arrival, participants initially performed a standardised warm-up of the right knee extensors, before completing three MVC to determine maximal force production. Participants then performed either a high or low demanding cognitive task, presented in a randomised and counterbalanced order. The effects of the cognitive tasks on physical endurance performance was subsequently assessed through a sub-maximal, isometric contraction of the knee extensors, performed within the minute following the end of the cognitive task, and sustained until task failure.

2.3. Cognitive Tasks

2.3.1. High Cognitive Demand Task (HIGH)

Protracted performance of a modified version of the Stroop task (Bohnen et al., 1992) was used to induce mental fatigue. The task consisted of a 32-minute block and then a 16-minute block (block 1 and 2), with a 10-min interval in-between (Figure 1). During the 10-minute interval, participants completed a heartbeat tracking task (e.g. Ring and Brener, 2016), for another study investigating interoception and autonomic nervous regulation. At the beginning and end of each block, participants were presented with 32 trials of the modified Stroop task, in order to assess cognitive function. Results from initial pilot work demonstrated the adopted task sufficiently induced and sustained elevated perceptions of fatigue. In the cognitive task, the words red, green, yellow and blue were continuously presented one at a time in red, blue, yellow and green coloured text on a black background. The task comprised two stimulus types. When the word was presented on its own, participants were asked to respond by pressing the key (coloured stickers were placed on the direction/navigation keys) that matched the colour of the text and not the word itself. However, when the word was bound by "!!", participants were asked to switch their target and respond to the word rather than the colour of the text. The two stimulus types were presented with equal frequency in a fully randomised order. The task consisted of both congruent (i.e. the colour of the text and the word matched) and incongruent (i.e. the colour of the text and word differed) trials. To prevent habituation of responses and maintain task engagement, the response keys for a given colour were changed between the 10th and 20th minute of the first block of the task, before returning to the original configuration. The cognitive task was programmed in Python using PsychoPy 3.0.2. (Peirce et al., 2019). Words were presented in the middle of the screen for 500 ms and participants had 1700 ms from stimulus presentation to make their response. There was a 2500-ms interval between the presentation of one word to the presentation of the next. Participants were asked to respond to the stimulus as quickly as possible. They were unaware of their performance during the task, with the accuracy of responses (i.e. correct or incorrect) and reaction time recorded automatically throughout. During the cognitive task(s), participants wore noise cancelling headphones and privacy screens were positioned to surround the participant in order to minimise distraction from any external stimuli.

2.3.2. Low Cognitive Demand Task (LOW)

LOW was designed to induce minimal mental fatigue. The task consisted of watching a documentary (*Planet Earth: The Shallow Seas*; Alastair Fothergill, 2006) over two consecutive blocks (block 1 and 2 of 32- and 16-min duration, respectively), separated by a 10-min interval, in keeping with the HIGH condition (Figure 1). To maintain participants engagement with the task, participants were instructed that they should press a direction/navigation key anytime they saw a coral reef within the documentary, in order to mimic the responses made in HIGH. As in the HIGH condition, at the beginning and end of each block, participants were presented with 32 trials of the modified Stroop task, in order to assess the effect of the low cognitively demanding tasks impact on cognitive function.

2.4. Physical Endurance Task

Physical performance was assessed through a sustained isometric contraction of the right leg at 20% of MVC, following the cognitive tasks as adopted by Pageaux et al. (2013). Bias ± 95% level of agreement of 4.7 ± 25.9% (Clark et al., 2007) and standard error of the mean (SEM) of 14.8% (Mathur et al., 2005) have been previously reported for this physical task. Submaximal force was determined from maximal force production during the familiarisation session and remained constant throughout the experimental manipulation. Maximal force did not differ between sessions ($F_{(1.33, 22.56)} = 0.113$, $p = 0.809$, $\eta p^2 = 0.007$) and the between-session coefficient of variation for maximal force was 5.6 ± 5.7%. Visual feedback of the target force and online force production were displayed on the computer positioned in front of the participant. Participants were asked to maintain the target force until task failure, defined as either three significant and consecutive drops in force below target or the inability to maintain the target force for >3 s. Participants were unaware of their performance time during the task and were only made aware upon completion of the study. Moreover, participants received no verbal encouragement during the physical task in order to minimise any potential experimenter bias.

2.5. Perceptual, Affective and Psychological Assessments

2.5.1. Perception of Effort and Affective valence

The perception of effort, defined as "*the conscious sensation of how hard, heavy and strenuous exercise is*" (Marcora, 2010) and affective valence were assessed every 30 s throughout the physical task, in pseudorandomized order. Perception of effort was measured using the Borg CR-10 scale (*see* Borg (1982), Borg (1998) for validation of the scale; Reliability: ICC > 0.8 (Shariat et al., 2019; Ljunggren et al., 1988)). Participants were instructed to disassociate feelings of pain and discomfort from the perception of effort, with effort representing how strenuous the exercise felt at a given point in time. Experiential anchors were set with 0 representing no effort and 10 the degree of effort felt during the strongest contraction they had previously experienced (max effort). Affective valence was assessed using the Feeling Scale (range +5 to -5; Hardy & Rejeski, 1989) with positive integers representing pleasurable affective states and negative integers unpleasurable affective states. The extremes of the scale were anchored based on experiential factors related to prior exercise experiences, with +5 representing individuals' most pleasant experience during previous physical activity and -5 their most unpleasurable experience.

2.5.2. Perceptions of Fatigue

The perception of fatigue was recorded using the rating of fatigue (RoF) scale (Micklewright et al., 2017). Ratings of fatigue were assessed before and immediately after each block of the cognitive tasks, providing four individual ratings within each session. As per the scale's authors definition, fatigue was defined as a "*feeling of diminishing capacity to cope with physical or mental stressors, either imagined or real"* (Micklewright *et al*., 2017). Instructions and anchoring procedures presented to participants conformed to the authors' original instructions.

2.5.3. Mood

Upon arrival, participants mood was assessed using the Brunel Mood Scale (Terry & Lane, 2003). Participants were asked to quantify their current mood state. This questionnaire contains 24 items divided into six subscales representing anger, confusion, depression, fatigue, tension, and vigour. Items were answered on a 5-point scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, and 4 = extremely), with each subscale comprising four individual items, enabling a score in the range of 0 to 16. The fatigue and vigour subscales were used to assess participants mood in relation to subjective fatigue before experimental conditions.

2.5.4. Motivation

Participants' motivation for the upcoming task was assessed before the first block of the cognitive task (PRE), before the second block (MID) and before the knee extensors' physical task (POST). Motivation was assessed using a visual analogue scale (VAS) (*e.g.* Tanaka et al., 2013). Participants were asked to place a mark intersecting a 10 cm line to express their current level of motivation towards the upcoming task, from 0 ('*Not motivated at all'*) to 10 ('*Extremely motivated'*).

2.6. Force Recording

Participants were seated, upright on a custom high-backed chair with hip and knee angles set at 90° (0° = full extension). The upper torso was secured to the back of the chair via two noncompliant cross-over shoulder straps, minimizing extraneous movement of the upper body. Contraction force of the right knee extensors was measured via a calibrated load cell (Model 615, Vishay Precision Group, Basingstoke, UK), secured to the lower leg via a cuff fastened slightly superior (2 – 4 cm) of the lateral malleoli, and attached to a custom-built bridge amplifier (Type 132-C, Datum Electronics, Isle of Wight, UK). The amplifier was connected to a data acquisition system (PowerLab 26T; ADInstruments, Oxfordshire, UK) and then digitised (LabChart v7.0, ADInstruments).

2.7. Data Analysis

For assessment of cognitive function, accuracy (% correct) and response time (s) were computed over 32 trials of the modified Stroop task performed at the beginning and end of each of the two blocks for both conditions using the original configuration keys (Figure 1). MVC force was defined as the greatest 500 ms across the total contraction duration.

2.8. Statistical Analysis

Statistical procedures were performed using Statistical Package for the Social Sciences (SPSS Inc., v25, Chicago, IL) unless stated otherwise. Gaussian distributions were verified using a combination of normal Q-Q plots and Shapiro-Wilk tests. Sphericity was assessed using Mauchly's test, with Greenhouse-Geisser correction applied as appropriate ($\varepsilon < .75$). Time to task failure (TTF), and initial mood (fatigue and vigour) were compared between cognitive tasks using a paired samples t-test. A condition [HIGH, LOW] x block [1, 2] x time [PRE, POST] repeated-measures ANOVA was used to test for the effect of the cognitive tasks on RoF, accuracy (% correct) and response time (s). Motivation was assessed using a condition [HIGH, LOW] x time [PRE, MID, POST] repeated-measures ANOVA. To account for the unbalanced data obtained due to individual differences in performance time, the perception of effort and affective valence reported during the knee extensors' contraction were analysed using a linear mixed model (LMM) in Jamovi (v. 1.6) through the *GAMLj* module (Gallucci, 2019). The perception of effort and affective valence were included as dependent variables in separate analyses, with fixed effects of condition (i.e. low- and high-cognitive demand), time and their interaction. Participants were entered as a random effect, with the intercept of the model allowed to vary between individuals. The model specification was: *effort/affect ~ condition + time + condition*time + (1|participant).* F-tests were computed for the fixed effects using Satterthwaite approximation of the degrees of freedom. The model was generated from time points in which recordings were obtained from both conditions. This led the exclusion of one data point for the high cognitive demand condition (0.005% of total data recorded). The fixed effect of condition was estimated using a simple contrast, with the effect of time estimated through analysing trends in means across time using polynomial contrasts. Pearson product correlations were used to assess the relationships between TTF and perceptual and affective responses within each condition, with the false discovery (FDR) rate adjusted for multiple comparisons (Benjamini & Yosef, 2000; Pike, 2011). Within-participant, repeated measures were used to assess the relationships between fatigue and the perceptual and affective responses during the physical endurance task, performed using the *rmcorr* package (Bakdash & Marusich, 2017) in R (R Core Team, 2018). This was performed to assess relationships across a larger range of subjective fatigue responses. Data for parametric analyses were reported as $M \pm SD$ while non-parametric analyses were reported as median (*Mdn*) plus interquartile range (*IQR*), unless otherwise stated. Effect sizes for main effects are presented as partial eta squared (η_p^2), while pairwise comparison of mean differences are presented as Cohen's d_{av} (Lakens, 2013). The null hypothesis was rejected at an α-level of 0.05.

3. Results

The two cognitive tasks were shown to have different effects on cognitive performance (Table 1). Task accuracy data was significantly different between the HIGH and LOW condition ($F_{(1,17)}$=19.834, p<.001, η_p^2=.54). Additionally, a time x condition interaction was found ($F_{(1,17)}$=5.067, p=.04, η_p^2=.23), with task accuracy significantly different between PRE and POST for the HIGH condition only (p=.05). No other significant effects were found (p<.05). Response times between the conditions were significantly different ($F_{(1,17)}$=9.665, p=.01, η_p^2=.36). Analysis of this effect revealed that response times were slower in HIGH compared with LOW. No other significant effects were found (p<.05).

On arrival, participants did not differ in their level of fatigue (LOW: 2 ± 2 *vs*. HIGH: 2 ± 3; $t_{(14)}$=-.21, p=.84, d_{av}=.05) nor vigour (LOW: 7 ± 3 *vs*. HIGH: 6 ± 4; $t_{(14)}$=.35, p=.73, d_{av}=.07) between conditions as assessed through BRUMS. The results for fatigue were confirmed through RoF: There was a significant effect of condition ($F_{(1,17)}$=9.546, p=.01, η_p^2=.36), time ($F_{(1,17)}$=71.801, p <.01, η_p^2 =.81), and block ($F_{(1,17)}$= 44.780, p<.01, η_p^2=.73), and a condition x time interaction ($F_{(1,17)}$=21.103, p=.01, η_p^2=.55). RoF was not significantly different between HIGH and LOW at baseline (p=.10). However, protracted engagement in the cognitive tasks resulted in significantly greater RoF in HIGH compared with LOW (p=.001, Figure 2). Motivation towards the upcoming task(s) was influenced by the type of cognitive task: there was a significant difference between the conditions ($F_{(1,17)}$=8.974, p=.01, η_p^2=.33), time ($F_{(1,17)}$=27.122, p<.001, η_p^2=.60), with a condition x time interaction ($F_{(2, 36)}$=4.198, p=.02, η_p^2=19). Motivation was not significantly different between conditions PRE (p=.29; d_{av}=.31) but was lower in HIGH *vs.* LOW at MID (p=.01; d_{av}=.93) and POST (p=.02; d_{av}=.75; Figure 3).

Endurance performance was not significantly different following LOW (172.1 ± 69.4 s) and HIGH (173.9 ± 74.6 s; $t_{(17)}$=-.32 p=.74, d_{av}=.03). The hierarchical analysis demonstrated no main effect of condition ($F_{(1,158)}$=0.238, p=.63, η_p^2=.001) or condition x time interaction ($F_{(9,158)}$=0.677, p=.73, η_p^2=.04) on the perception of effort. There was however a main effect of time ($F_{(9,158)}$=77.949, p<.001, η_p^2=.82). Analysis of the trends in the estimated fixed effect demonstrated that, on average, the perception of effort increased over time (linear effect: estimate=6.42 [5.51, 7.34], t=13.73, p<.001), however the rate of this increase appeared to lessen as endurance performance progressed (quadratic effect: estimate=-1.84 [-2.65, -1.03], t=-4.44, p<.001; see Figure 4.). Full description of the estimated fixed effects and random effects evident for the perception of effort are presented in *Supplementary Table 1*. Similar results were evident for affective valence recorded during the physical endurance task. There was no main effect of condition ($F_{(1,159)}$=0.422, p=.52, η_p^2=.003) nor interaction between condition x time ($F_{(9,158)}$=0.850, p=.57, η_p^2=.05). There was however, a main effect was evident for the effect of time

($F_{(9,159)}$=28.196, p<.001, η_p^2=.62). Estimation of the fixed effect of time demonstrated a linear decrease across time (linear effect: estimate=-6.28 [-7.55, -5.01], t=-9.68, p<.001; see Figure 5). Full description of the estimated fixed and random effects evident for affective valence is presented in *Supplementary Table 2*.

No correlations between perceptual/affective responses and endurance performance were evident following LOW (all p>0.05). However, following HIGH, physical endurance performance was correlated with both perceptions of effort (r=-.55, p=.047) and affective valence (r=.61, p=.037) recorded during the initial stages of the task (i.e. 60 s). RoF recorded on completion of HIGH was not correlated with endurance performance (r=-.02, p=.86). Across conditions, RoF displayed a positive relationship with perceived effort (r_{rm}=.52 [95% CI: -.19 – .47], p=.004) and a negative relationship with affective valence (r_{rm}=-.59 [95% CI: -.54 – .04], p<.001).

4. Discussion

The aim of the present study was to assess the hypotheses that (1) a prolonged, demanding cognitive task exerts a negative influence on subsequent physical endurance performance and (2) the perception of fatigue is associated with changes in perceptual (i.e. effort) and affective processing. The results of the present study demonstrate that engagement in prolonged cognitive activity did not negatively impact participants' physical endurance performance. Despite participants displaying impaired cognitive performance and reporting greater subjective perceptions of fatigue, conventional markers of a state of mental fatigue, the capacity to sustain the physical endurance task and the subjective perceptual/affective responses to the task did not differ between the high and low cognitive demand conditions. There was a relationship between the perception of fatigue and effort and affective responses during the physical task, which may support the perception of fatigue as a significant influence on perceptual and affective processing during task performance.

As presented, it has been proposed that the type of physical task used to probe the effect of prior cognitive activity influences its emergence (Giboin & Wolff, 2019). Here, we adopted a sustained, single limb contraction, believed to be most sensitive to the posited detrimental effects and in turn conceptually replicated one of the core studies in the present literature (Pageaux et al., 2013). The high-demand cognitive task induced a state of "mental fatigue", characterised by poorer cognitive performance and an increased perception of fatigue. However, in contrast to the findings of Pageaux and colleagues (2013), associated fatigue effects did not alter endurance performance within the physical domain. The result was relatively surprising given the size of the effect reported by Pageaux and colleagues (d_{av} = 1.49), which fell beyond the inherent measurement error associated with the adopted physical endurance task (Clark et al., 2007; Mathur et al., 2005). In keeping with other studies, Pageaux and colleagues (2013) reported that impairment to physical endurance performance following prior cognitive activity was associated with alterations to how effortful the physical task was perceived to be, which influences decisions made during activity (Pageaux, 2014). Our results do not support this contention. The neurophysiological basis of effort, and its perception, is an area of much interest but mechanistic uncertainty regarding what exactly drives the cost of effort (see Inzlicht et al., 2018; Kurzban, 2016; Shenhav et al., 2017). Furthermore, it remains unclear whether effort experienced across cognitive and physical domains represents a complimentary experience and shared underpinnings (see Shenhav et al., 2017), or may be separated. The present findings may align closer to a separation of these neural processes. Beyond effort, recent evidence has indicated that of greater importance may be the level of arousal and affective valence experienced by the load imposed on cognitive control (Ávila-Gandía et al., 2020). In relation to the latter, in the present study, demanding cognitive activity did not change affective experiences reported during the physical endurance task. Together, the results of the present study add to a body of evidence indicating that a state of mental fatigue following prior cognitive activity may not impair subsequent physical endurance performance, in line with recently expressed concerns about the effect (Holgado, Sanabria, et al., 2020).

It is important to acknowledge that the present study was not a full replication of Pageaux and colleagues' (2013) original study, differing in the adopted cognitive task and the method for assessing the perception of fatigue. Such differences, particularly the adopted cognitive intervention, may limit full comparison and account for contrasting performance effects (see Van Cutsem, Marcora, et al., 2017). The subjective experience of fatigue incurred by a given task may also vary considerably between individuals. In the present study, a third of the sample reported the perception of fatigue to be of similar intensity at the end of low and high cognitive demand task. This may indicate that for certain individuals, the high cognitive demanding task may not have been sufficient to evoke a perceived challenge to one' capacity to cope with task demands (i.e. the definition of fatigue used here) and may speak to a proposed "*underload/overload*" hypothesis associated with emotional responses to cognitive tasks (Pattyn et al., 2008). The level of arousal or challenge experienced in response to a cognitive activity may distinguish, for example, the experience of boredom (i.e. underload) from fatigue (i.e. overload). In addition to fatigue, Thompson and colleagues (2020) recently demonstrated that the modified Stroop task may incur some feelings of boredom, which may be due to the monotony of the task or possibly insufficient cognitive processing duration set by the parameters of the task, such that participants disengage from the task (e.g. Borragán et al., 2019). More nuanced assessment of the perceptual constructs evoked through cognitive exertion are required in future to separate fatigue from other psychological constructs. Moreover, we agree with recent propositions that cognitive tasks should be individualised in order to try to match cognitive demand experienced across all participants when studying the development of fatigue (O'Keeffe et al., 2020). It is worth noting also that a small, but non-significant change in the perception of fatigue was evident across the low cognitive demand task. This is not uncommon with such tasks (O'Keeffe et al., 2020), but does offer the possibility that performance effects may be masked by a deleterious effect of fatigue (or other states of arousal) in both conditions. Given how small this effect was, it is likely that this had little impact on the observed responses (or lack thereof) during subsequent physical performance, despite an increased subjective perception of fatigue.

Though the present study failed to observe physical performance impairment associated with a state of mental fatigue, the results may still offer some information concerning the potential nature and function of the perceptual component of fatigue. The perception of fatigue was elevated by the high demand cognitive task, but the perception of effort (and affective valence) recorded during the subsequent physical task was not, offering a partial dissociation between perceptual constructs. Further disassociation of constructs was evident based on associations with endurance performance following the high cognitive demand task, with endurance performance correlated with perceptions of effort during the task but not with the state of perceived fatigue. A common feature of many fatigue studies is the disassociation between the perception of fatigue and performance fatigability (Enoka & Duchateau, 2016). Benoit et al. (2019) propose that the perception of fatigue signals an anticipation of future adverse consequences on the brain's resources with continued activity. If tasks are continued, further investment of effort may eventually be required to compensate the possible decrease in resources able to be dedicated to task performance (Benoit et al., 2019). Of interest, the correlation between effort (and affective valence) and endurance performance was evident only after the high cognitive demand task in the present study, which may indicate that a heightened state of fatigue serves to sharpen the appraisal of task demands, not necessarily alter it. In our previous study, we evidenced complex emotional-cognitive interactions in the regulation of physical endurance performance, with perception of fatigue correlated with both perception of effort and affective valence during the physical task (Greenhouse-Tucknott et al., 2020). Similar associations were reported by Harris and Bray (2019) following a cognitive task, indicating a possible common function of the perception of fatigue across both acute physical and cognitive performance. Here, across both conditions, the perception of fatigue was correlated with the perception of effort and affect valence recorded during the initial stages of the physical endurance task. We do acknowledge that the bootstrapped CI suggests that considerable uncertainty was evident in this effect. Nevertheless, this may indicate that the perception of fatigue, independent of its domain of origin, may exert some influence on perceptual and affective processes used to guide behaviour. This fits with the proposed meta-cognitive foundations of fatigue (Hockey, 2011; Müller & Apps, 2019; Stephan et al., 2016). Future studies are required to identify the neural structures supporting the distinct percepts (i.e. fatigue *vs*. effort) and their interactions in relation to behavioural regulation. We also continue the call for greater specificity in the measures and terminology used in the description of fatigue, effort and behavioural regulation (Greenhouse-Tucknott et al., 2020; Halperin & Emanuel, 2020).

5. Conclusion

In conclusion, demanding cognitive activity serves to impair cognitive performance and elevates the subjective perception of fatigue, conforming to previous definitions of a state of "mental fatigue". However, this did not translate to performance impairment nor influence perceptual and affective responses during a task of physical endurance. The findings of the present study therefore fail to support contentions of detrimental effect of prior cognitive activity on subsequent physical endurance performance. Though physical endurance performance was not impaired, relationships between the perception of fatigue and effort/affective responses during the physical task suggest that the state perception of fatigue may exert some influence on perceptual and affective responses used to guide behaviour.

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Figure 1. Schematic of experimental design. BRUMS: Brunel mood scale. MVC: Maximal voluntary contraction. RoF: Ratings of fatigue. Motiv. VAS: Motivation visual analogue scale. HIGH: High demand cognitive task. LOW: Low demand cognitive task. KE: Knee extensors.

Figure 2. Change in ratings of fatigue (RoF) in response to cognitive interventions. Circles represent individual data points, while pale lines represent the change in mean (± SD) before (PRE) and after (POST) each block of the cogntive intervntions. LOW: low demand cognitive task (blue circles and lines), HIGH: high demand cognitive task (red circles and lines).

Figure 3. Change in motivation in response to cognitive interventions. Motivation recoreded using a 10 cm visual analogue scale (VAS). Circles represent individual data points, while pale lines represent the change in mean (± SD) before (PRE) and after (POST) each block of the cogntive intervntions. LOW: low demand cognitive task (blue circles and lines), HIGH: high demand cognitive task (red circles and lines).

Figure 4. Change in the perception of effort during the knee extensor endurance task following the LOW and HIGH cognitive demand interventions. Data presented as individual data points (circles) with the change in the mean response of each condition tracked by the pale lines. In keeping with the hierarchical analysis, all time points included in which responses in both conditions were evident. LOW: low demand cognitive task (blue circles and lines), HIGH: high demand cognitive task (red circles and lines).

Figure 5. Change in affect during the knee extensor endurance task following the LOW and HIGH cognitive demand interventions. Data presented as individual data points (circles) with the change in the mean response of each condition tracked by the pale lines. In keeping with the hierarchical analysis, all time points included in which responses in both conditions were evident. LOW: low demand cognitive task (blue circles and lines), HIGH: high demand cognitive task (red circles and lines).