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Heart rate biofeedback attenuates effects of mental fatigue on exercise performance

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ABSTRACT

Objective: Cognitive control exertion increases mental fatigue and impairs subsequent physical performance. Few studies have investigated intervention strategies to attenuate the effects of mental fatigue on exercise behavior. This study examined heart rate (HR) biofeedback as a moderator of the effects of mental fatigue on vigorous-intensity exercise performance.

Design: Within-subjects, crossover design.

Methods: Participants ($N = 36$) completed four 20-min sessions of self-paced, cycling exercise. Exercise was preceded by 10-min high or low cognitive control manipulations crossed with HR biofeedback or no feedback during exercise in a 2 (high vs. low cognitive control) X 2 (biofeedback vs. no feedback) factorial arrangement. Participants rated their intended rating of perceived exertion (RPE) and goal commitment prior to and following the cognitive control manipulations. HR and total work were recorded during each exercise session.

Results: Mental fatigue was significantly greater following high cognitive control exertion, which corresponded with significant reductions in intended RPE and goal commitment. Participants exercised at a lower average HR and performed less work in the high cognitive control/no feedback condition, however, with HR biofeedback following high cognitive control exertion participants attained similar HRs and total work performed to the low cognitive control conditions, which did not differ.

Conclusions: HR biofeedback improves self-regulation of exercise behavior in a mentally fatigued state. Without biofeedback, fatigued people may down-regulate exercise intensity. Findings have implications for the use of HR-monitoring devices to improve intensity-based exercise prescription adherence when confronted with barriers such as mental fatigue.

For over a decade, public health agencies have endorsed physical activity (PA) guidelines that recommend adults engage in at least 150 min of moderate-to-vigorous intensity PA (MVPA) weekly (Haskell et al., 2007). Moderate-intensity activities (e.g., brisk walking, active involvement in games/sports) involve 3–6 times the amount of energy one expends while resting, whereas vigorous-intensity activities (e.g., running, competitive involvement in games/sports) expend > 6 times of that of rest. However, despite being aware of the importance of regular participation in MVPA (Martin, Morrow, Jackson, & Dunn, 2000) and having goals to be more active (Godin & Conner, 2008), behavioral surveillance data show only ~20% of North American adults are able to meet these recommendations (Clark, Norris & Schiller, 2017; Public Health Agency of Canada, 2016).

Research has identified several common barriers to participation in MVPA, which include lack of time, limited access to facilities, and fatigue (Salmon, Owen, Crawford, Bauman, & Sallis, 2003). However, despite its recognition as a barrier to MVPA, little research attention has been devoted to understanding or developing strategies to overcome fatigue. Fatigue has been defined as "a disabling symptom in which physical and cognitive function is limited by interactions between performance fatigability and perceived fatigability (Enoka & Duchateau, 2016, p. 3); thus having physiological and psychological components. Population data show perceived fatigue is a prevalent symptom in modern society (Aritake et al., 2015), particularly among post-secondary students (American College Health Association, 2015) and the adult workforce (Ricci, Chee, Lorandeau, & Berger, 2007).

Although the prevalence of perceived fatigue may be high in the population, low rates of PA cast doubt on physical energy expenditure as the cause of fatigue symptoms. However, another common manifestation of perceived fatigue is mental fatigue, which may play an important role in fatigue symptomology and as a deterrent to PA. Mental fatigue is a complex psychophysiological phenomenon that

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results in feelings of tiredness or lack of energy, associated with exposure to cognitively-effortful tasks including tasks that require cognitive control (Boksem & Tops, 2008). Cognitive control is an aspect of self-control involving cognitively-mediated processes that enable inhibition of unwanted responses or activation of goal-directed thoughts or behaviors (Inzlicht, Bartholow, & Hirsh, 2015). Cognitive control is fundamental to people's abilities to alter or maintain many health-related behaviors such as avoiding temptations to cheat on a diet or sticking to an exercise regimen (De Ridder, Lensvelt-Mulders, Finkenauer, Stok, & Baumeister, 2012). However, exerting cognitive control is effortful (Botvinick & Braver, 2015) and has been shown to have a medium-sized effect on perceptions of fatigue ($d = 0.44$) and behavior ($d = 0.62$) (Hagger, Wood, Stiff, & Chatzisarantis, 2010). A recent meta-analysis revealed that cognitive control tasks also have a medium to large negative carryover effect on performance of subsequent tasks requiring effortful cognitive control and that mental fatigue may mediate these effects (Clarkson, Otto, Hassey, & Hirt, 2016).

The focus of this study was on the effects of mental fatigue on exercise, however, it is important to recognize research investigating mental fatigue has much in common with research on ego-depletion (Englert, 2016). Ego-depletion refers to a phenomenon in which exerting self-control on an initial task leads to impairments in people's abilities to exert further self-control on a subsequent task (Friese, Loschelder, Gieseler, Frankenbach, & Inzlicht, 2018). Studies in both areas have employed cognitive manipulations (e.g., Stroop task) and physical performance measures (e.g., time to exhaustion tests) that are identical or share fundamental cognitive (e.g., response inhibition) and physical requirements (e.g., aerobic exercise; isometric exercise). Ego depletion and mental fatigue have been described as "essentially the same" by some researchers (Inzlicht & Berkman, 2016, p. 514), yet others have argued there are fundamental differences (Vohs, Glass, Maddox & Markman, 2010). Given our specific focus on participants' subjective ratings of mental fatigue brought on by performing cognitive tasks, we elected to frame and interpret the current research in terms of mental fatigue rather than ego-depletion (although we respect some researchers or readers may choose to do otherwise).

Cognitive control and mental fatigue have received limited empirical attention as they relate to PA epidemiology or adherence (Englert & Rummel, 2016; Rebar, Dimmock, Rhodes, & Jackson, 2018; Schöndube, Bertrams, Sudeck, & Fuchs, 2017), yet a considerable body of evidence points to mental fatigue as a factor that impairs exercise performance (cf. Reviews by Englert, 2016 and Van Cutsem et al., 2017). However, findings from this body of literature are largely derived from samples of active individuals or trained athletes and, thus, may have limited generalizability to other segments of the population who are inactive or active at levels lower than those recommended by public health guidelines. Furthermore, the exercise tasks performed in these studies (e.g., cycling until exhaustion, isometric endurance) are quite dissimilar to the types of PA most people engage in for health benefits.

In one recent study, Brown and Bray (2018) investigated the effects of a mentally-fatiguing cognitive control task on people's motivation and behavior for engaging in a 30-min bout of MVPA in a sample of participants who were not sufficiently active (i.e., not engaging in ≥ 150 min/week of MVPA). Results revealed participants cycled almost 1 km (850 m) less distance and exercised at an average heart rate of ~ 8 beats per minute lower in the mental fatigue condition compared to a rested control condition. These findings suggest that intervention strategies could be developed that would better enable self-regulation of exercise when people are mentally fatigued.

Self-regulation refers to altering unwanted thoughts, feelings and actions to align with norms, goals and standards (Baumeister & Vohs, 2016). Behavior change techniques that target theory-based motivational and self-regulatory factors shown to facilitate behavioral control should be integral to the design of interventions (Michie & Johnston, 2012), which applies to interventions that would aim to alter the negative effects of mental fatigue on PA. One prominent theory of self-regulation is control theory (Carver & Scheier, 1982). Control theory proposes a cybernetic structure wherein self-regulation of behavior is enabled through a process of setting a goal and monitoring behavior using feedback to adjust goal-behavior discrepancies and facilitate goal attainment. Consistent with the predictions of control theory, laboratory studies examining the aftereffects of effortful cognitive control have shown that providing participants with performance-based feedback enables goal maintenance and attenuates negative carryover effects that are otherwise observed from one cognitively-demanding task to another (Voce & Moston, 2016; Wan & Sternthal, 2008). However, to this point, no research has investigated the potential for biofeedback to modify the effects of mental fatigue on exercise perceptions and behavior.

Investigating the effects of goals, self-monitoring, and feedback on exercise behavior stands to be informative and also holds promise for widespread application as self-monitoring tools (e.g., HR monitors, activity trackers) that provide objective individualized feedback are commonplace (Macridis, Johnston, Johnson, & Vallance, 2018), but may not be systematically used for these purposes. Moreover, HR-based exercise prescription guidelines can be used as a reference value (goal) to promote goal-directed behavior. Therefore, HR biofeedback may be an effective method for regulating goal-directed exercise via adherence to prescribed target HR zones.

In addition to examining the effects of biofeedback on exercise behavior, research is also needed to identify psychological mechanisms that may play moderating or mediating roles in the relationship between mental fatigue and exercise performance. Motivation has been theorized to account for the negative aftereffects of cognitive control exertion on behavioral regulation (Inzlicht & Schmeichel, 2012), however, a major criticism of motivational accounts is that self-report measures of task and intrinsic motivation have failed to explain performance impairments associated with cognitive control or mental fatigue in several studies (Brown & Bray, 2017a; MacMahon, Schücker, Hagemann, & Strauss, 2014; Marcora, Staiano, & Manning, 2009; Pageaux, Lepers, Dietz, & Marcora, 2014). An alternative operationalization of motivation involves assessing changes in how much effort people are willing to invest in exercise when they feel fatigued. For example, in the study by Brown and Bray (2018) mentioned previously, the researchers discovered that performing a demanding cognitive control task for 50 min caused reductions in participants' effort-based intentions prior to beginning to exercise. Comparatively, when participants performed a task involving low cognitive control demands (i.e., watching a documentary video) for 50 min there were no changes in effort-based intentions. These results align with previous work by Martin Ginis and Bray (2010) and support the idea that decreases in exercise performance under these circumstances may be associated with conscious motivational processes.

Another aspect of motivation that may be an important factor determining why people's effort-based intentions and performances change when they are mentally-fatigued is goal commitment. Goal commitment refers to one's determination to achieve a goal and has been shown to moderate the relationship between goal-setting and goal-directed behaviors (Klein, Wesson, Hollenbeck, & Alge, 1999). Several factors have been shown to affect goal commitment (Locke, Latham, & Erez, 1988), however, the effects of mental fatigue on commitment to exercise performance goals have not been investigated. For both intentions and commitment, receiving biofeedback may engage brain regions responsible for effortful control (e.g., prefrontal cortex, anterior cingulate cortex, anterior insula) that help attenuate shifts in motivation by increasing the salience or clarity of one's goals despite internal perturbations such as fatigue (Müller & Apps, 2018).

The overarching purpose of this study was to examine biofeedback as a moderator of the relationship between mental fatigue and performance of a vigorous-intensity PA regimen. Based on findings from the literature (Englert, 2016; Van Cutsem et al., 2017), we predicted that performing a cognitive task requiring high cognitive control exertion would cause increases in mental fatigue and reductions in exercise performance compared to a control task that did not require cognitive control or induce mental fatigue. Based on Control Theory (Carver & Scheier, 1982) and evidence from the performance feedback literature (Voce & Moston, 2016; Wan & Sternthal, 2008), it was predicted that receiving HR biofeedback would attenuate declines in performance such that when people were mentally-fatigued, they would exercise at the same intensity and perform the same amount of work as when not mentally fatigued. The secondary purpose was to examine the effects of mental fatigue on motivational perceptions related to exercise. In line with previous findings (e.g., MacMahon et al., 2014; Marcora et al., 2009), it was hypothesized that high cognitive control exertion would not lead to changes in task or intrinsic motivation, but would lead to lower levels of intended exercise intensity (Brown & Bray, 2018; Martin Ginis & Bray, 2010) and decreased commitment to exercise goals.

1. Method

1.1. Participants and design

Participants were 36 university students (16 males, 20 females) with a mean age of 19.44 ($SD = 1.42$) and a mean BMI of $M = 22.86 \pm (SD = 3.55)$; including underweight ($n = 3$), normal ($n = 27$), overweight ($n = 3$), and obese ($n = 3$) participants. A sample size estimate was computed using G*Power software (Version 3.1; www.gpower.hhu.de), based on McMorris, Barwood, Hale, Dicks and Corbett's (2018) meta-analysis effect size of cognitive control manipulations on physical performance (Hedge's $g = 0.27$). According to G*Power estimates, 36 participants were required for our primary analysis using a 4 condition, repeated measures, within-subject design with $\beta = 0.95$ and $\alpha = 0.01$, Inclusion criteria specified participants had intentions to meet, but were not currently meeting American College of Sports Medicine (ACSM, 2013) PA recommendations of ≥150 min of MVPA per week in the past 6 months, which was confirmed by self-reported weekly MVPA ($M = 103.19 \pm 30.19$ min). All participants were pre-screened for contra-indicators of performing moderate-to-vigorous intensity exercise using the Physical Activity Readiness Questionnaire (PAR-Q; Thomas, Reading, & Shephard, 1992). An example item is, "Do you have a medical condition that requires you to avoid strenuous exercise?" If participants answered "No" to all questions within the PAR-Q they were informed they were eligible for the study and provided informed consent.

To mask the primary hypotheses, the study was advertised as "*a brief, vigorous-intensity exercise training intervention consisting of eight exercise sessions, in which feelings and behavior during training would be examined under a variety of conditions*". Couched within the eight sessions, the study employed a single-blind, 2 (high vs. low cognitive control) X 2 (biofeedback vs. no feedback) cross-over design during sessions 3 to 6. To control for potential order effects, a Williams Latin-square was used (Williams, 1949). Participants were randomized in equal numbers to four possible sequences of the four conditions, with each condition preceded once by each other condition and occurring once in each randomization sequence (i.e., ABDC, BCAD, CDBA, DACB). Participants were instructed to avoid consuming caffeinated products prior to testing and to get at least 8 h of devoted rest the night before their study session. Participants confirmed adherence to these requirements prior to each session. An institutional research ethics board reviewed and approved the study.

1.2. Measures

1.2.1. Demographics, MVPA and anthropometrics

Demographic information for self-reported sex, age, and average weekly MVPA were obtained for descriptive purposes and to confirm eligibility. The International Physical Activity Questionnaire (Craig et al., 2003) was used to assess weekly minutes of MVPA during the 6 months prior to the study. Anthropometric data (height and weight) were obtained using a calibrated weigh scale and tape measure and used to calculate BMI (mass(kg)/height(m)^2).

1.3. Exercise protocols

1.3.1. Graded cardiovascular exercise test (GXT)

All participants completed a GXT on a cycle ergometer (Lode Corival, Groningen, The Netherlands) during Sessions 1 and 8. The GXT served two purposes. The first was to mask the primary hypotheses, serving as pre- and post-training assessments of cardiovascular performance to evaluate the "training" intervention. The second was to determine participants' peak HR (HR_{PEAK}) achieved during the pre-test GXT in order to determine their target HR (% of HR_{PEAK}) during the 20-min exercise training sessions. The GXT consisted of a 3-min warm-up at 50 Watts (W) resistance at > 50 RPM, after which resistance was automatically increased by 1 W/2 s until volitional exhaustion. The ergometer was set in hyperbolic (rpm-independent) mode to ensure the workload was constant throughout the GXT regardless of pedaling speed. Participants achieved a mean HR_{PEAK} of 185.00 ($SD = 9.69$) for the GXT performed during Session 1.

1.3.2. Self-paced exercise training sessions

Participants completed six, 20-min, self-paced bouts of exercise on a cycle ergometer at a self-determined cadence > 50 RPM. Sessions began with a 3-min warm-up at 50 W resistance. At the end of the warm-up, the experimenter switched the ergometer to manually adjustable linear (rpm-dependent) mode and set the workload to a nominal resistance level ($\alpha = .025$) and instructed participants they were in control of the workload throughout the exercise session using the up/down buttons on the ergometer controller. Upon completion of the 20-min exercise session, the ergometer was re-set to a workload of 50 W and participants performed a 3-min cool down. For exercise in linear mode, workload (W) was determined by the formula: $W = \alpha * (RPM)^2$; where workload is the product of pedaling cadence (RPM) and the resistance level "α" selected by participants.

1.4. Cognitive control experimental manipulations

The cognitive control task manipulations were delivered in a structured 12-min window consisting of five 2-min task blocks each separated by a 30-s break, in which participants provided ratings of mental fatigue.

1.4.1. High cognitive control (HCC) task

Participants performed a computerized version of the incongruent color-word Stroop task (Stroop, 1935) using Presentation™ software (Version 17.0; NBS www.neurobs.com). The incongruent Stroop task requires high levels of response inhibition, a central component of cognitive control, which is a primary reason why this manipulation has been used to induce mental fatigue in several investigations (e.g., Pageaux et al., 2014; Brown & Bray, 2017a, 2017b). This version of the Stroop task has been shown to reliably induce mental fatigue and lead to reduced persistence on an isometric handgrip endurance task (Brown & Bray, 2017a; 2017b). Each 2-min block consisted of 135 trials. The word stimuli (i.e., BLACK, BLUE, GREEN, RED, PINK, GRAY) were presented on a white background in 48-size, Times New Roman font on a 17″ computer monitor. Stimuli were visible on the monitor for 800-ms followed by a 100-ms inter-trial interval in which the screen was blank. Participants were instructed to respond as quickly and accurately as possible to each stimulus by saying aloud the color of the font in which the word was printed while ignoring the printed word (e.g., for the word "black" presented in the color red, they would say aloud the word "red").

1.4.2. Low cognitive control (LCC) task

Participants watched five, 2-min segments of a documentary film (*Planet Earth: Fresh Water*; Fothergill, Attenborough, & Fenton, 2007) on a 17" computer monitor. Passive control tasks such as number viewing are associated with boredom and heightened perceptions of fatigue (Milyavskaya, Inzlicht, Johnson, & Larson, 2018), therefore to control for potential changes in psychological factors that could influence physical performance, participants were asked to monitor the audio commentary and recorded instances when they heard a key word: "*water*". Previous studies using this attention-control task have shown it results in stable, low levels of mental fatigue and no changes in affective valance or arousal during 10-min of exposure (Brown & Bray, 2017a, 2017b; Zering, Brown, Graham, & Bray, 2017).

1.5. Biofeedback manipulations

To conform to overarching efforts to use common language across literature, we have operationalized the manipulation of providing HR feedback while exercising as "Biofeedback" as per Michie et al.'s (2015) definition: "Providing feedback about the body (e.g., physiological or biochemical state) using an external monitoring device as part of a behavior change strategy." Michie and colleagues taxonomy of behavior change techniques identified "biofeedback" as one of five behavior change techniques that constitute the cluster "Feedback and monitoring." During exercise sessions 3 to 6, participants wore a HR monitoring chest strap device under the ruse that HR biofeedback was going to be used in each of the sessions. However, in two of the sessions the experimenter informed participants the device was malfunctioning and would not be able to provide HR information, while in the other two sessions HR information was available.

1.5.1. Biofeedback present

For the "biofeedback" conditions, continuous HR feedback was transmitted from a Polar HR monitor (Polar H7) and presented visually on a Polar watch (Polar T1) affixed to the wall directly in view in front of the participant while they exercised.

1.5.2. Biofeedback absent

For the "no feedback" conditions, participants were informed the HR monitor was malfunctioning and received no HR feedback while they exercised.

1.6. Psychological variables

1.6.1. Mental demand

Participants rated how mentally demanding each of the cognitive control manipulations was using the Mental Demand item of the National Aeronautics and Space Administration Task Load Index: NASA TLX (Hart & Staveland, 1988). The single-item measure is rated on a 20-point scale with bipolar descriptors ranging from (*very low*) to (*very high*).

1.6.2. Mental fatigue area under the curve (AUC)

A Visual Analogue Scale (VAS; Wewers & Lowe, 1990) was used to assess mental fatigue at four intervals during, and upon completion of the cognitive control manipulations. Participants were instructed: "Please mark the point on the line that represents your current state of mental fatigue" and were asked to draw an 'X' at the point along a 100 mm line with the anchors ranging from 0 (*none at all*) on the left hand side and 100 (*maximal*) on the right hand side. Scores were calculated by measuring the distance (in mm) the 'X' was placed from the left side of the scale. To assess the cumulative effect of the experimental manipulations over the 10-min period, the five mental fatigue scores were summed to calculate the AUC.

1.6.3. Intrinsic motivation

Five items from the effort and importance subscale of the Intrinsic Motivation Inventory (Ryan, 1982) were used to assess intrinsic motivation. Each item was prefaced with the stem, "For the exercise task I am about to do …" An example item is, "I am going to put a lot of effort into this." Items were rated on a 7-point Likert scale ranging from 1 (*not true at all*) to 7 (*very true*). Internal consistency was acceptable at each administration (Cronbach's $\alpha \geq 0.84$).

1.6.4. Task motivation

Task motivation was measured using a VAS (Wewers & Lowe, 1990). Participants were asked: "For the exercise task you are about to complete, please mark the point on the line that represents your current state of motivation" and asked to place an 'X' at the point along a 100 mm line with the anchors ranging from 0 (*none at all*) on the left to 100 (*maximal*) on the right. Scores were calculated by measuring the distance (in mm) the 'X' was placed from the left side of the scale.

1.6.5. Intended physical exertion (Intended RPE)

Participants rated their intended RPE for each 20-min exercise session using Borg's (1998) 6 (*no exertion at all*) to 20 (*maximal exertion*) RPE scale and were encouraged to use decimal points to indicate partial numbers (e.g., 14.5). Following the methodology of Martin Ginis and Bray (2010), Intended RPE was assessed prior to and following each of the cognitive control manipulations.

1.6.6. Goal commitment

Klein, Wesson, Hollenbeck, Wright and DeShon's (2001) five-item scale was used to measure goal commitment. An example item is, "I am strongly committed to pursuing this goal." For each item, participants rated their commitment to an identified session objective of exercising at a vigorous-intensity (RPE ranging between 14 and 17 or 75–95% HR_{PEAK}) on a 5-point scale ranging from 1 (*strongly disagree*) to 5 (*strongly agree*). Goal commitment was assessed prior to and following each cognitive control manipulation. Internal consistency was acceptable at each administration (Cronbach $\alpha \geq 0.80$).

1.6.7. RPE

Participants rated perceived exertion using Borg's (1998) 6 (*no exertion at all*) to 20 (*maximal exertion*) RPE scale. Ratings were obtained at 1-min intervals during each of the 20-min exercise sessions and scores were averaged to compute the variable: RPE_{AVE} for each session.

1.7. Physiological variables

1.7.1. HR

HR was recorded continuously throughout each of the GXTs, 20-min exercise training sessions, and the 10-min cognitive manipulations using a Polar HR monitor (Polar H7) which transmitted continuous HR data to an iPad where it was recorded using the Polar Beat application (Version 2.4; www.polar.com). HR_{PEAK} was established as the highest HR achieved during the GXT and used to individualize participants' HR target zone prescriptions for exercise as per ACSM (2013) HR-based guidelines. Average percentage of HR_{PEAK} ($PEAKHR\%_{AVE}$) was calculated by averaging the HR values computed over one-minute intervals during the 20-min exercise protocols, and then dividing by each participant's HR_{PEAK}. $COG\text{-}HR_{AVE}$ was calculated by averaging the HR values computed over one-minute intervals during the 10-min experimental manipulation window.

1.7.2. Total work

The amount of accumulated energy (kJ) was calculated by the Lode Ergometry Manager software (Version 10) for each 20-min exercise training session.

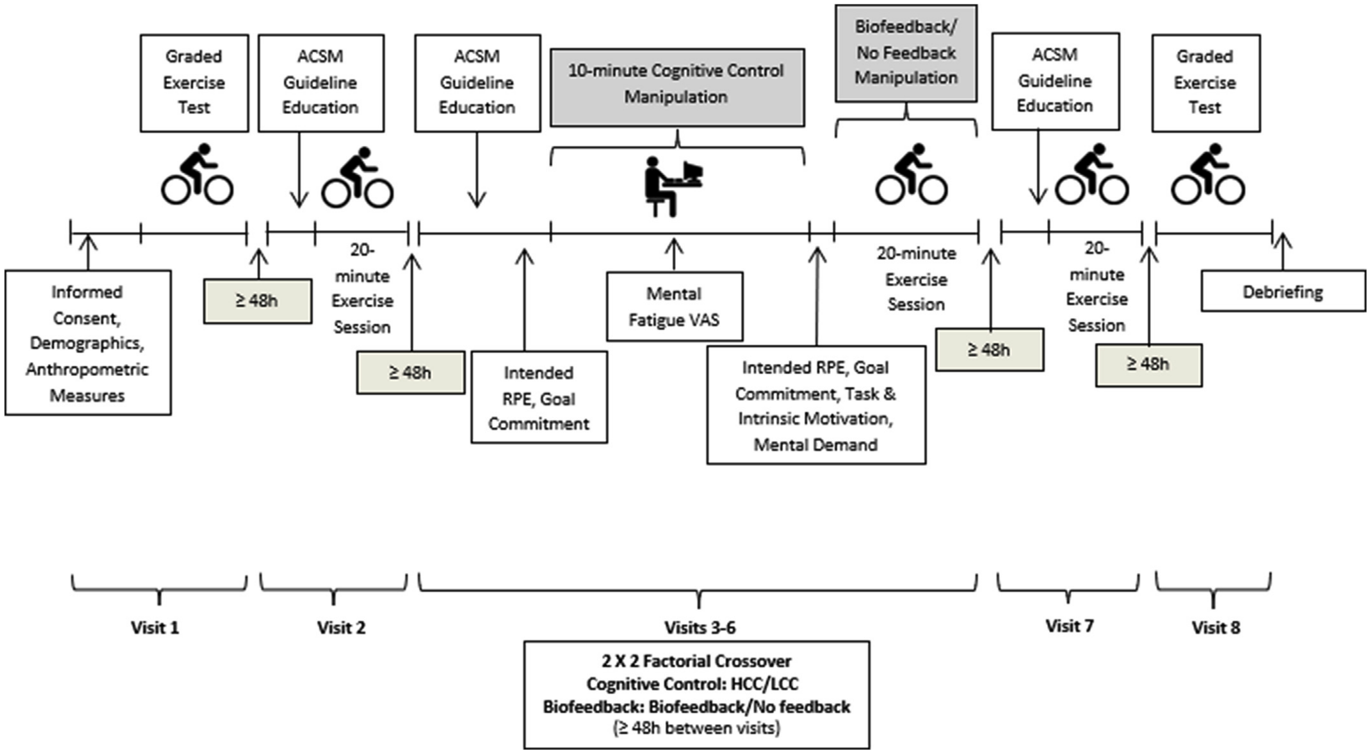

Fig. 1. Study procedures timeline.

1.8. Procedure

Participants attended eight laboratory sessions (see Fig. 1 for Procedure Timeline). Upon arrival at the laboratory for Session 1, participants completed the PAR-Q (Thomas et al., 1992), provided informed consent and completed the demographic and PA questionnaires. Height and weight were recorded, and participants were fitted with a HR monitor. Participants then mounted the cycle ergometer and completed a GXT.

Session 2 served as a familiarization session for the self-paced exercise sessions. Upon arrival at the laboratory, participants were fitted with a HR monitor and instructed how to use the RPE scale following instructions provided by Borg (1998, p. 47). Next, the experimenter directed participants' attention to the current ACSM (2013) PA prescription guidelines for vigorous-intensity cardiorespiratory exercise pertaining to RPE (i.e., RPE of 14–17) and HR (i.e., 75–95% of HR_{MAX}), which were printed on 8.5 × 11 laminated paper and affixed to the wall in front of the cycle ergometer, and confirmed participants' understanding of the content. Participants were then instructed their goal was to exercise according to these guidelines for 20 min during each of the six "training" sessions involved in the study. Next, participants mounted the cycle ergometer and performed the first self-paced exercise session without HR feedback and reported RPE at one-minute intervals throughout the task.

Prior to Session 3, participants were randomized to one of four crossover variations using a Williams Latin square design. Sessions 3 to 6 followed identical procedures, with participants completing the cognitive control and HR biofeedback manipulations in accordance with their assigned treatment sequence. At the start of each session, participants were fitted with a HR monitor, reminded of the ACSM (2013) vigorous-intensity exercise guidelines for HR and RPE, and completed the Intended RPE and Goal Commitment measures. Participants then performed their assigned cognitive control manipulation providing ratings of Mental Fatigue at each 2-min interval. Upon completion of the cognitive control task, they provided a rating of Mental Fatigue and completed the Mental Demand measure. Next, they completed the Intended RPE and Goal Commitment measures again, as well as the Intrinsic Motivation and Task Motivation measures for the upcoming exercise bout. As per the cross-over design, participants were then either given access to feedback from the HR monitor or no HR feedback (one session with biofeedback and one without feedback for each cognitive control condition) and performed a self-paced exercise session reporting RPE at 1-min intervals.

Session 7 was identical to Session 2. During Session 8, participants completed the post-training GXT and were debriefed upon its completion. Each study session was scheduled at approximately the same time of day with no less than 48 h between sessions to allow time for recovery. Throughout the sessions, experimenters interacted with participants to provide instructions, to take measures, and to ensure the safety of participants. Any form of motivational encouragement was deliberately withheld at all times. Participants were remunerated upon completion of each laboratory session ($10 for each session and a $20 bonus upon completion of Session 8 for completing the full study).

1.9. Data analysis

Descriptive statistics were computed for all study variables. A paired samples *t*-test was computed as a manipulation check to assess changes in cognitive performance from block 1 to block 5 on the Stroop task. A series of separate 2 (Cognitive Control) X 2 (Biofeedback) repeated measures ANOVAs were computed to evaluate differences in Mental Fatigue AUC, $COG\text{-}HR_{AVE,}$ Intrinsic Motivation, Task Motivation and Mental Demand to evaluate the effects of the cognitive control manipulations. Separate 2 (Cognitive Control) X 2 (Biofeedback) X 2 (Time) repeated measures ANOVAs were computed to compare differences in Intended RPE and Goal Commitment for the cognitive control manipulations. To decompose interaction effects, separate paired samples *t*-tests with Bonferroni corrections were computed to examine changes in Intended RPE and Goal Commitment over time for the HCC and LCC conditions, respectively. Separate effect sizes (Cohen's *d*) were calculated for Intended RPE and Goal Commitment scores for the LCC and HCC conditions with adjustment for correlations between pairs of measures (Morris & DeShon, 2002). In any analysis where the biofeedback manipulations had not yet occurred, the main and interaction effects of Biofeedback were redundant and therefore not reported.

For the main analyses, separate 2 (Cognitive Control) X 2 (Biofeedback) repeated measures ANOVAs with post-hoc (Bonferroni) tests were computed to compare differences in $PEAKHR\%_{AVE}$, total work, and RPE_{AVE}. Estimated effect sizes for all analyses are reported as partial eta squared (η_p^2). All statistical analyses were performed using IBM SPSS version 20.

2. Results

2.1. Cognitive performance

A paired samples *t*-test revealed a significant increase in the number of incorrect responses from the first block to the last block of the Stroop task for the HCC manipulation (t (71) = 6.62, $p < .001$, $d = 0.84$, $M_{Change} = 8.03 \pm 10.28$). Declines in performance on the HCC task provide a secondary objective indicator of mental fatigue (e.g., Boksem, Meijman, & Lorist, 2005).

2.2. Intrinsic motivation

Analyses of intrinsic motivation values (Table 1) showed no differences between the Cognitive Control conditions, F (1, 35) = 0.07, $p = .80$, $\eta_p^2 = 0.00$.

2.3. Task motivation

Analyses of task motivation values (Table 1) showed no significant difference between the Cognitive Control conditions, F (1, 35) = 3.54, $p = .07$, $\eta_p^2 = 0.09$.

2.4. Mental demand

NASA-TLX mental demand scores (Table 1) indicate the HCC task required significantly greater mental demand compared to the LCC task, F (1, 35) = 967.44, $p < .001$, $\eta_p^2 = 0.97$.

2.5. Mental fatigue AUC

Results showed significantly higher ratings of mental fatigue during the HCC task compared to the LCC task, F (1, 35) = 67.73, $p < .001$, $\eta_p^2 = 0.66$ (Table 1).

2.6. $COG\text{-}HR_{AVE}$

Results showed significantly greater average HR during the HCC task compared to the LCC task, F (1, 35) = 32.73, $p < .001$, $\eta_p^2 = 0.48$ (Table 1).

3. Main analyses

3.1. Effects of cognitive control experimental manipulations on pre-exercise psychological variables

3.1.1. Intended RPE

Analyses of pre- and post-cognitive control manipulation ratings of intended RPE (Table 1) showed non-significant main effects of Cognitive Control, F (1, 35) = 1.14, $p = .29$, $\eta_p^2 = 0.03$, and Time, F (1, 35) = 1.40, $p = .25$, $\eta_p^2 = 0.04$, but a significant interaction, F (1, 35) = 7.24, $p = .01$, $\eta_p^2 = 0.17$. Decomposing the interaction using paired *t*-tests of the pooled means for the HCC and LCC conditions with a Bonferroni correction (adjusted $\alpha = 0.025$) revealed a significant decrease in intended RPE scores in the HCC conditions, t (71) = 2.50, $p = .02$, $d = -0.30$, but no change in the LCC conditions, t (71) = −1.58, $p = .12$, $d = 0.18$.

3.1.2. Goal commitment

Analyses of pre- and post-cognitive control manipulation ratings for goal commitment (Table 1) revealed significant main effects of Cognitive Control, F (1, 35) = 4.99, $p = .03$, $\eta_p^2 = 0.13$, Time, F (1, 35) = 12.89, $p = .001$, $\eta_p^2 = 0.27$, and Cognitive Control × Time interaction, F (1, 35) = 17.09, $p < .001$, $\eta_p^2 = 0.33$. Decomposing the interaction using paired *t*-tests with a Bonferroni correction (adjusted $\alpha = 0.025$) of the pooled means for the HCC and LCC conditions showed a significant decrease in goal commitment in the HCC conditions, t (71) = 4.78, $p < .001$, $d = -0.59$, but no change in the LCC conditions, t (71) = 0.38, $p = .71$, $d = 0.04$.

3.2. Effects of experimental manipulations on heart rate, behavior, and RPE during exercise

3.2.1. $PEAKHR\%_{AVE}$

Values for $PEAKHR\%_{AVE}$ for the exercise sessions are presented by condition, in Fig. 2. Results revealed significant main effects for Cognitive Control, F (1, 35) = 12.22, $p = .001$, $\eta_p^2 = 0.26$, Biofeedback, F (1, 35) = 20.70, $p < .001$, $\eta_p^2 = 0.37$, and a Cognitive Control × Biofeedback interaction, F (1, 35) = 15.24, $p < .001$, $\eta_p^2 = 0.30$. Post-hoc planned contrasts (Bonferroni) were computed between each condition to decompose the interaction, which showed participants exercised at virtually-identical heart rates ($ps = > 0.99$) in the LCC/no feedback, LCC/biofeedback, and HCC/biofeedback conditions, while during the HCC/no feedback condition they exercised at a significantly lower HR than each of the other conditions ($ps < .001$).

Table 1
Descriptive statistics for psychological measures following the cognitive control experimental manipulations by condition.

Measures	Condition (*N* = 36)			
	LCC *M* (*SD*)	LCC + BF *M* (*SD*)	HCC *M* (*SD*)	HCC + BF *M* (*SD*)
Intrinsic Motivation	5.92 (.79)	5.80 (.89)	5.86 (.96)	5.89 (.75)
Task Motivation	68.39 (20.84)	69.17 (19.87)	64.92 (20.59)	64.22 (19.87)
Mental Demand	1.89 (.78)	2.19 (1.41)	15.08 (3.58)	15.86 (2.33)
Mental Fatigue AUC	125.82 (81.49)	122.92 (86.66)	262.72 (112.16)	250.19 (104.26)
$COG\text{-}HR_{AVE}$ (bpm)	78.80 (11.95)	79.16 (12.27)	85.25 (11.37)	85.72 (13.04)
Intended RPE Pre	15.50 (1.46)	15.25 (1.34)	15.29 (1.30)	15.50 (1.24)
Intended RPE Post	15.56 (1.46)	15.32 (1.33)	15.19 (1.49)	15.28 (1.30)
Goal Commitment Pre	4.41 (.53)	4.23 (.64)	4.39 (.55)	4.24 (.69)
Goal Commitment Post	4.41 (.55)	4.21 (.66)	4.18 (.73)	4.04 (.79)

Note. LCC = low cognitive control; HCC = high cognitive control; BF = biofeedback; AUC = area under the curve representing mental fatigue over 10-min of the cognitive control manipulations; $COG\text{-}HR_{AVE}$ = average heart rate over 10 min of the cognitive task experimental manipulation; Pre = pre-cognitive task; Post = post-cognitive task.

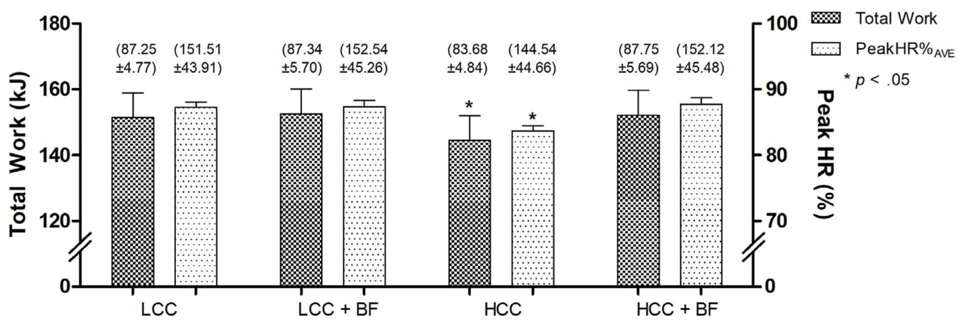

Fig. 2. Average percentage of peak heart rate and total work performed during exercise by condition. Bars represent standard error. Nummerical text above bars represent M ± SD.* indicates values for Total Work and HR Peak (%) for HCC differ significantly ($p > .05$) from the other conditions. All other condition-condition values are significantly different ($p > .05$).

3.2.2. Total work

Accumulated energy (kJ) for each of the exercise sessions is displayed, by condition, in Fig. 2. Results revealed significant main effects for Cognitive Control, F (1, 35) = 11.21 $p = .002$, $\eta_p^2 = 0.24$, Biofeedback, F (1, 35) = 9.96, $p = .003$, $\eta_p^2 = 0.22$, and a significant interaction, F (1, 35) = 5.23, $p = .028$, $\eta_p^2 = 0.13$. Decomposition of the interaction using post-hoc planned contrasts (Bonferroni) between each condition revealed significantly lower total work in the HCC/no feedback condition compared to both LCC conditions ($ps \leq .002$) and the HCC/biofeedback condition ($p = .004$). However, there were no differences between any of the LCC/no feedback, LCC/biofeedback and HCC/biofeedback conditions ($ps > .99$).

3.2.3. RPE_{AVE}

RPE_{AVE} values for the four conditions were as follows: LCC/no feedback ($M = 14.53 \pm 1.09$), LCC/biofeedback ($M = 14.70 \pm 1.32$), HCC/no feedback ($M = 14.42 \pm 1.28$), and HCC/biofeedback ($M = 14.99 \pm 1.75$). Analyses showed a significant main effect of Biofeedback, F (1, 35) = 5.40, $p = .03$, $\eta_p^2 = 0.13$), with greater RPE in the biofeedback conditions. The main effect for Cognitive Control, F (1, 35) = 0.43, $p = .52$, $\eta_p^2 = 0.01$, and the Cognitive Control × Biofeedback interaction were not significant, F (1, 35) = 2.01, $p = .17$, $\eta_p^2 = 0.05$.

4. Discussion

The purpose of the present study was to investigate biofeedback as a potential moderator of the relationship between mental fatigue and performance of a vigorous-intensity PA regimen. In line with previous findings (e.g., Brown & Bray, 2017a; Marcora et al., 2009), we found that performing a task requiring high cognitive control exertion significantly increased ratings of mental fatigue and led to reductions in the amount of work performed during a vigorous-intensity exercise session compared to a control task consisting of watching a documentary film. However, this is the first study to show that receiving HR biofeedback during exercise attenuates the negative effects of mental fatigue on exercise performance. Additional evidence showed intended physical exertion and goal commitment were reduced when participants were mentally-fatigued, which could explain reductions in performance in the HCC/no-feedback condition, but not when participants matched their non-fatigued performances when they received HR biofeedback.

A growing literature has consistently documented negative carryover effects of performing mentally-fatiguing cognitive tasks on a variety of tasks requiring physical stamina (Van Cutsem et al., 2017). Although the literature has focused largely on active samples, the present findings bolster recent research (Brown & Bray, 2018) showing detrimental effects of mental fatigue on people's motivation and volitional energy expenditure while performing PA that aligns with intensity-based exercise prescription guidelines. These findings provide further evidence that mental fatigue may be a serious and influential impediment to intensity-based exercise prescription adherence that has yet to grasp the attention of researchers and health promotion practitioners.

While the negative effects of cognitive control exertion or mental fatigue on physical performance have been seen in past studies, to the best of our knowledge, this is the first study to show that people who are provided with HR-based biofeedback while exercising are able to achieve similar levels of performance to those accomplished when exercising in a non-fatigued state. These findings support previous studies investigating carryover effects of cognitive-control fatigue on performance of cognitive tasks (Voce & Moston, 2015; Wan & Sternthal, 2008). Together, the results suggest that having clear goals and accessible performance feedback makes goal progress more salient and helps people effectively self-regulate their physical or cognitive behavior when they are mentally-fatigued and might otherwise experience performance lapses.

Our hypotheses that biofeedback would attenuate negative effects of mental fatigue on exercise behavior were guided by Control Theory (Carver & Scheier, 1982), which stresses the importance of using feedback to drive goal-directed behavior to align with standards, and proposes these processes create a motivational structure that supports self-regulation. Without all of these factors intact, perturbations such as fatigue may interfere with behavioral regulation because attention may more easily shift away from the target behavior. However, as Müller and Apps (2018) have argued, reward or reinforcement stimuli should heighten awareness of goals and increase attention on goal-related processes that help to maintain attention towards goal pursuit. Consistent with this idea, evidence indicates offering incentives attenuates negative carryover effects of mental fatigue on physical and cognitive performance (Brown & Bray, 2017b; Luethi et al., 2016). The current findings suggest biofeedback may also serve to sustain or re-direct attention towards performance goals and increase goal salience. Interestingly, both Brown and Bray (2017b) and the current study showed no effects of incentives or biofeedback when they were available to participants when they were not mentally-fatigued. These findings also align with control theory inasmuch as people in a non-fatigued state should not require incentives or biofeedback to up-regulate effort to pursue their original goal, but rather incentives and feedback information provide reinforcement to sustain performance at the level of the goal.

Control theory provides a cognitive-behavioral framework in which to situate the present findings. However, recent neurophysiological research examining fatigue also identifies substrates and network activation patterns that may provide mechanistic accounts for the current results. That is, a consistent body of research has revealed engaging in tasks requiring effortful cognitive control leads to changes in activation within brain regions (i.e., dorsolateral prefrontal cortex, dorsal anterior cingulate cortex and anterior insula) known to play a fundamental role in monitoring fatigue and effort-based decision making (cf. Müller &

Apps, 2018). In an illustrative study by Pires et al. (2018), participants engaging in a 30-min effortful cognitive control task exhibited alterations in prefrontal cortex activation as evidenced by increased Fp1 EEG theta power which remained hyperactivated during performance of a subsequent 20 km cycling time trial, resulting in a 2.7% performance reduction and exacerbated perceptions of exertion while performing the trial. Given the role of the prefrontal cortex in goal-directed behavior, EEG patterns witnessed in that study may reflect impaired willingness to maintain effortful control, ultimately resulting in down-regulation of exercise performance.

In another study, Luethi et al. (2016) observed decreased prefrontal activation in participants while performing a thought suppression task, which was associated with impaired performance on a Stroop task performed shortly thereafter. As mentioned above, Leuthi et al. showed that offering a performance-contingent incentive restored performance to levels participants had accomplished in a non-fatigued state. What is interesting from those results is that offering incentives led to up-regulation of neural activity in the prefrontal regions that had previously been down-regulated following the thought-suppression task. Although we did not monitor brain activation in the current study, it seems plausible that similar neurological effects in prefrontal regions associated with effortful control could be observed in response to mental fatigue and biofeedback and should be investigated in future research.

Although our primary focus was on the behavioral effects associated with mental fatigue and HR biofeedback, psychological perceptions recorded during the different exercise sessions also showed interesting trends and deserve attention. For instance, in the two no-feedback conditions, participants provided equivalent RPE ratings in both the mental fatigue and no-fatigue conditions despite exercising at a significantly lower workload and HR in the mental fatigue condition. Van Cutsem et al. (2017) have documented a common trade-off between perceived exertion and how much work is performed when people exercise in a mentally-fatigued state. That is, if RPE is constant, work performed goes down; if work is constant, RPE goes up. Thus, mental fatigue appears to enhance internal cues signaling exertion and bias RPE while people are attempting to regulate exercise behavior.

The similar levels of RPE that occurred in the mental fatigue condition that did not receive biofeedback is also interesting to interpret in light of the fact that there was a significant reduction in HR that accompanied lower workload. These findings suggest autonomic nervous system inputs are not integrated into the RPE/workload associations that are observed when people are mentally fatigued. Contrary to Borg, Hassmen and Lagerstrom’s (1987) original research fitting an HR algorithm to the 6–20 RPE scale, Nicolò, Marcora, and Sacchetti (2016) have shown that respiratory rate shows stronger and more reliable correlations with RPE than HR during exercise. Future research should more thoroughly investigate cardiorespiratory variables that covary with RPE during exercise to determine whether respiratory patterns are affected by mental fatigue in a manner that would explain why RPE is high despite lower work and HR.

The current findings support previous work showing task and intrinsic motivation do not change in response to mental fatigue (e.g., MacMahon et al., 2014; Marcora et al., 2009). However, exercise intentions and goal commitment decreased significantly in response to mental fatigue. Given the small magnitude of change in each of these variables (i.e., < 1 scale increment), it is difficult to argue these factors have strong explanatory influence on the association between mental fatigue and exercise performance. Nonetheless, these findings provide support for motivational accounts of self-control (e.g., the Process model) and have implications for future research as well as application to exercise promotion. Future studies should begin to probe more complex motivational processes involved in people's decision making such as qualitative investigation of what people attribute adjustments to intentions or commitment to. It would also be informative to examine the experiences people report (e.g., think aloud) while exercising when they are mentally-fatigued and how those experiences may differ from exercising in a rested state or how they may be altered when they receive biofeedback. Past research by MacMahon et al. (2014) has also found that mental fatigue can lead to an increased internal focus of attention. Future research should further investigate psychophysical responses to exercising with and without biofeedback as people's responses such as affective feeling states may differ when feedback leads them to exercise at higher intensities than they would engage in without feedback (Parfitt, Rose, & Burgess, 2006).

In terms of application, practitioners should consider assessing mental fatigue levels prior to, and during exercise, and recognize that mental fatigue may heighten perceived exertion and lead to greater discomfort while exercising. Also, it is important to recognize we found a 5% performance impairment (i.e., total work and $PEAKHR\%_{AVE}$) associated with mental fatigue that was corrected by receiving biofeedback. With these findings in mind, practitioners may stress the importance of using biofeedback to their clients, as it may be a simple and cost-effective way to help exercisers get more out of the time they spend exercising. Because adaptations to exercise are intensity-dependent (Swain & Franklin, 2006), using HR-based feedback could help ensure people achieve exercise intensities consistent with target HR zones recommended to confer optimal cardio-protective benefits. Biofeedback may also aid weight management by countering reductions in energy expenditure when people down-regulate exercise intensity in response to mental fatigue and translate into reduced risk for comorbid conditions (e.g., hypertension, type 2 diabetes) associated with overweight and obesity (Khaodhiar, McCowen, & Blackburn, 1999). Moving forward, future research investigating whether the effects of biofeedback are efficacious outside controlled, laboratory environments deserves attention.

The present study advances knowledge of the effects of mental fatigue on exercise performance in numerous ways; however there are several limitations that should be noted. For instance, the sample was a homogenous group of insufficiently active, young adults who had intentions to become more active, which limits generalizability to the broader population. Because fatigue increases with age (Butt et al., 2010), it would be worthwhile to examine whether effects observed in this study are more pronounced among middle age and older adults. Furthermore, using a 10-min Stroop task to induce mental fatigue may not be representative of the cognitive control demands individuals experience performing tasks that may induce mental fatigue in academic or occupational environments. Cognitively-demanding experimental manipulations must eventually give way to tasks that have greater ecological validity in order to better determine the effects of mental fatigue on people's motivations, perceptions, and behaviors relevant to intensity-based exercise prescription adherence. It also should be acknowledged that having people cycle on a stationary bike at a vigorous intensity for a brief duration limits the extent to which the current findings may generalize to exercise performed at moderate-to-vigorous intensities that are the focus of public health recommendations (Haskell et al., 2007). Studies involving a range of exercise intensities, modes, and durations should be undertaken to determine the extent to which the current findings may generalize to a broader representation of exercise behaviors. Finally, given the nature of the experimental environment (e.g., providing monetary incentives for participation, having an experimenter present to observe behavior), it is possible that participants’ RPE scores may have been influenced by social desirability. That is, they may have reported biased ratings that met the assigned exercise intensity even if they did not perceive that level of physical exertion, which could explain why there was no interaction for RPE despite a significant interaction being observed for the objective performance variables.

This study contributes to the rapidly developing literature examining the effects of mental fatigue on exercise performance and is the first to demonstrate using objective HR-based biofeedback attenuates the negative effects of mental fatigue on exercise performance. Results support predictions of control theory in that having a goal (i.e., HR-based target zones) and receiving relevant objective biofeedback (i.e., HR) facilitates behavioral regulation when feeling mentally-fatigued and experiencing reduced exercise motivation. Implementation of biofeedback based interventions may have widespread implications for improving the efficiency of vigorous-intensity PA regimens as many people deal with mental fatigue on a daily basis.

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Declarations of interest

None.

Author declaration

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We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We further confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address (brownd32@mcmaster.ca) which is accessible by the Corresponding Author and which has been configured to accept email.

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