MENTAL FATIGUE AND PHYSICAL ACTIVITY BEHAVIOUR

MENTAL FATIGUE AND SELF-REGULATION OF PHYSICAL ACTIVITY BEHAVIOUR

By DENVER MITCHELL YURKO BROWN
B.Sc.Kin (Hons), M.Sc.

A Thesis

Submitted to the School of Graduate Studies

In Partial Fulfillment of the Requirements

For the Degree

Doctor of Philosophy

DOCTOR OF PHILOSOPHY (2018) McMaster University

(Kinesiology) Hamilton, Ontario

TITLE: Mental fatigue and self-regulation of physical activity behaviour

AUTHOR: Denver M. Y. Brown
B.Sc.(Hons) (McMaster University), M.Sc. (McMaster University)

SUPERVISOR: Dr. Steven R. Bray, Ph.D.

NUMBER OF PAGES: xvi, 202

LAY ABSTRACT

Effortful cognitive control exertion can lead to mental fatigue and impair self-regulation of subsequent physical performance. However, current understanding is limited due to a number of factors. This thesis addressed several gaps in the literature through a systematic examination of potential mediators and moderators of the mental fatigue - physical performance relationship. Findings revealed downstream physical performance impairments are dependent on exceeding a critical mental fatigue threshold. Reductions in pre-exercise cognitions including self-efficacy, intended physical exertion and goal commitment all correspond with negative changes in exercise performance. Evidence also highlights the generalizability of fatigue-induced effects by demonstrating that insufficiently active people engaging in exercise for health and fitness benefits down-regulate exercise performance in the face of mental fatigue. Incentives and heart rate biofeedback can attenuate the effects of mental fatigue on physical performance. Collectively, evidence provides insight for theories of self-control and can be interpreted within Muller and Apps (2018) neurocognitive framework of motivational fatigue.

ABSTRACT

Exerting cognitive control can lead to mental fatigue and impair self-regulation of subsequent physical performance. However, current understanding is limited due to a number of factors. First, studies have employed manipulations involving either high or low cognitive demands, failing to test whether a dose-response relationship exists between mental fatigue and physical performance. Second, the role of several psychological variables among the mental fatigue – physical performance relationship remains unclear. Third, current literature lacks generalizability in that existing findings have largely been derived from studies involving active samples performing physical tasks that the general population may not commonly engage in for health and fitness benefits. Lastly, there has been little research examining intervention strategies that may attenuate the effects of mental fatigue on physical activity behaviour. This dissertation aimed to advance our understanding of self-regulation of physical activity behaviour in response to mental fatigue by addressing shortcomings within the literature discussed above.

Study 1 examined whether a dose-response relationship exists for mental fatigue and physical performance. Results showed a performance threshold exists between 4 and 6 minutes of exposure to a mentally fatiguing cognitive control task. Beyond this threshold, task self-efficacy also showed uniform reductions which mediated the mental fatigue – physical performance change relationship. Findings are consistent with previous research and reveal self-efficacy is a key variable that accounts for the negative effects of mental fatigue on physical performance.

Study 2 investigated the hypothesis that offering a performance contingent monetary incentive would attenuate the negative carryover effects of mental fatigue on physical performance. Findings showed mental fatigue caused characteristic declines in physical performance; however, incentives countered the effects of mental fatigue and led to performances equal to those witnessed in a non-fatigued state. Interestingly, incentives did not provide any additional benefit for performance when not fatigued. Findings support motivational accounts of self-regulation, although incentives may lack practicality and may not be a cost-effective means to alter exercise behaviour.

Study 3 examined the effect of mental fatigue on intended physical exertion and exercise performance reflective of current public health guidelines for physical activity in a sample comprised of insufficiently active university students. Findings showed mental fatigue alters the amount of physical effort people are willing to invest in an exercise workout and follow through with those intentions by doing less work and exercising at a lower heart rate intensity. These are the first results showing people may deliberately adjust their physical effort to cope with mental fatigue.

Study 4 investigated whether heart rate biofeedback moderates the effects of mental fatigue on vigorous-intensity exercise reflective of current public health physical activity guidelines and the effects of mental fatigue on pre-exercise motivational cognitions. Results showed mental fatigue was associated with decreases in intended physical effort and commitment to vigorous-intensity exercise goals which corresponded with reductions in exercise intensity (i.e., HR_{AVE}) and total work performed when people exercised without feedback. However, HR biofeedback attenuated the negative carryover effects of mental fatigue on exercise behaviour, restoring exercise intensity and performance to levels witnessed in a non-fatigued state. Similar to incentives, biofeedback offered no further benefits for performance when not fatigued. Findings align with predictions of Control Theory and suggest biofeedback using widely available physical activity monitors in combination with goals can improve intensity-based physical activity guideline adherence when confronted with barriers such as mental fatigue.

ACKNOWLEDGEMENTS

First of all, I want to thank my supervisor Dr. Steven Bray for all his support and continuous guidance over the past 6 years. There are not many professions that people can choose who they work with, but I made a great choice when I decided to learn from you. You have provided me with outstanding mentorship during my M.Sc. and Ph.D. and helped me develop the fundamental skills necessary to not only succeed in academia, but also in life. It has been a privilege and an honour working with you as well as traveling to conference destinations and spending time together on the golf course. As I prepare to move on from McMaster, I hope this is just the beginning of a lifelong friendship as colleagues.

I also want to extend a big thank you to my advisory committee, Dr. Kathleen Martin Ginis and Dr. Jennifer Heisz; your contributions have been instrumental to my success throughout this process. You’ve both played a key role in encouraging my academic pursuits and I hope I reflect your passion as I enter the next phase of my career.

It would have been a challenge to get through graduate school without all the help and encouragement from my lab mates, colleagues, faculty and staff at McMaster. My time at McMaster has been filled with countless memories that I will not soon forget. To my academic big brothers, Jeff Graham and Paul Saville, I appreciate all your advice along the way.

To my family and friends - thank you for always being there for me. Mom and Dad, I am grateful for all the sacrifices you have made to ensure that I have had every opportunity to succeed in this life. Thank you for always listening and being there to celebrate my achievements with me.

Lastly, I want to thank my beautiful wife Rachel. You’ve provided me with unconditional support through the ups and downs of graduate school and helped me realize my true potential. I surely would not be the man I am today if it wasn’t for you. I look forward to the next stage in our journey through life together. I love you.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

FIGURES

CHAPTER 2: Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance

CHAPTER 3: Effects of mental fatigue on physical endurance performance and muscle activation are attenuated by monetary incentives

CHAPTER 4: Effects of mental fatigue on exercise intentions and behavior

CHAPTER 5: Heart rate biofeedback attenuates effects of mental fatigue on physical activity performance

TABLES

CHAPTER 2: Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance

CHAPTER 3: Effects of mental fatigue on physical endurance performance and muscle activation are attenuated by monetary incentives

CHAPTER 4: Effects of mental fatigue on exercise intentions and behavior

CHAPTER 5: Heart rate biofeedback attenuates effects of mental fatigue on physical activity performance

LIST OF ABBREVIATIONS

ACSM	american college of sports medicine
ANCOVA	analysis of covariance
ANOVA	analysis of variance
APA	american psychological association
AUC	area under the curve
AX-CPT	ax-continuous performance test
BMI	body mass index
CAD	Canadian dollars
CI	confidence interval
DOI	digital object identifier
EEG	electroencephalography
EMG	electromyography
FS	Feeling scale
GXT	graded exercise test
HCC	high cognitive control
hr	hours
HR	heart rate
Hz	hertz
Intended RPE	intended physical exertion
k^2	kappa-squared
kJ	kilojoules
LCC	low cognitive control
η_p^2	partial eta squared
m	meters
M	mean
min	minutes
mm	millimeters
ms	milliseconds
MVC	maximum voluntary contraction
MVPA	moderate-vigorous physical activity
NASA-TLX	national aeronautics and space administration task load index
PA	physical activity
PAR-Q	physical activity readiness questionnaire
PET-PEESE	precision-effect test and precision-effect estimate with standard errors
RPE	rating of perceived exertion
RPM	revolutions per minute
s	seconds
SD	standard deviation
SE	standard error
SPSS	statistical package for the social sciences
VAS	visual analogue scale
W	watts

PREFACE
DECLARATION OF ACADEMIC ACHIEVEMENT

This thesis is prepared in the “sandwich” format as outlined in the School of Graduate Studies’ Guide for the Preparation of Theses. It includes a general introduction, four independent studies prepared in journal article format, and a general discussion. The candidate is the first author on all of the manuscripts. At the time of the thesis preparation, Chapter 4 was in press (advance online publication) and Chapter 5 was under peer-review.

CONTRIBUTION TO PAPERS WITH MULTIPLE AUTHORSHIP

Chapter 2 (Study 1)

Brown, D. M. Y. & Bray, S. R. (2017). Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance. *Sport, Exercise and Performance Psychology, 6,* 355-369. DOI:10.1037/spy0000091

D. M. Y, Brown's role in Study 1:

- Conceived the research question and study design
- Author of ethics application at McMaster University
- Contributed to study design and measure selection
- Lead investigator responsible for data collection, analysis and interpretation
- Primary author of manuscript

Role of co-author in Study 1:

- SB provided feedback about the study design and obtained funding
- SB assisted DB with obtaining ethics approval at McMaster University
- SB assisted DB with the analysis and interpretation of the data
- SB provided critical feedback on previous drafts of the manuscript
- SB revised the article and approved of the final version of the manuscript before submission to the journal *Sport, Exercise and Performance Psychology*.

Chapter 3 (Study 2)

Brown, D. M. Y. & Bray, S. R. (2017). Effects of mental fatigue on physical endurance performance and muscle activation are attenuated by monetary incentives. *Journal of Sport and Exercise Psychology*, *39*, 385-396. DOI:10.1123/jsep.2017-0187

D. M. Y, Brown's role in Study 2:

- Conceived the research question and study design
- Author of ethics application at McMaster University
- Contributed to study design and measure selection
- Lead investigator responsible for data collection, analysis and interpretation
- Primary author of manuscript

Role of co-author in Study 2:

- SB reviewed and refined the study design and obtained funding
- SB assisted DB with obtaining ethics approval at McMaster University
- SB assisted DB with the analysis and interpretation of the data
- SB provided critical feedback on previous drafts of the manuscript
- SB revised the article and approved of the final version of the manuscript before submission to the *Journal of Sport and Exercise Psychology*.

Chapter 4 (Study 3)

Brown, D. M. Y. & Bray, S. R. (In Press) Effects of mental fatigue on exercise intentions and behavior. *Annals of Behavioral Medicine*. Advance online publication. DOI:10.1093/abm/kay052

D. M. Y, Brown's role in Study 3:

- Conceived the research question and study design
- Author of ethics application at McMaster University
- Contributed to study design and measure selection
- Lead investigator responsible for data collection, analysis and interpretation
- Primary author of manuscript

Role of co-author in Study 3:

- SB provided feedback about the study design and obtained funding
- SB assisted DB with obtaining ethics approval at McMaster University
- SB assisted DB with the analysis and interpretation of the data
- SB provided critical feedback on previous drafts of the manuscript
- SB revised the article and approved of the final version of the manuscript before submission to the journal *Annals of Behavioral Medicine.*

Chapter 5 (Study 4)

Brown, D. M. Y. & Bray, S. R. (Under Review). Heart rate biofeedback attenuates effects of mental fatigue on physical activity performance. Manuscript submitted to the journal *Psychology of Sport and Exercise*.

D. M. Y, Brown's role in Study 4:

- Conceived the research question and study design
- Author of ethics application at McMaster University

- Contributed to study design and measure selection
- Lead investigator responsible for data collection, analysis and interpretation
- Primary author of manuscript

Role of co-author in Study 4:

- SB provided feedback about the study design and obtained funding
- SB assisted DB with obtaining ethics approval at McMaster University
- SB assisted DB with the analysis and interpretation of the data
- SB provided critical feedback on previous drafts of the manuscript

CHAPTER 1:

INTRODUCTION

1.1 Physical Activity and Associated Benefits for Adults

North American public health agencies recommend adults engage in at least 150 minutes of moderate-to-vigorous physical activity (MVPA) or 75 minutes of vigorous physical activity weekly to promote and maintain health (Garber et al., 2011; Haskell et al., 2007). Accruing sufficient levels of physical activity provides a wide range of benefits including reduced risk for a number of chronic diseases (Penedo & Dahn, 2005; Warburton, Nicol & Bredin, 2006), improved mental health (Biddle & Asare, 2011; Lawlor & Hopker, 2001; Paluska & Schwenk, 2000) and enhanced cognitive and physical functioning (Bherer, Erickson & Liu-Ambrose, 2013; Cadore, Rodríguez-Mañas, Sinclair & Izquierdo, 2013; Chang, Labban, Gapin & Etnier, 2012).

Health promotion efforts have been successful at improving the population's awareness of the importance of meeting physical activity guidelines (Martin, Morrow, Jackson, & Dunn, 2000). For example, data indicate most people have goals or intentions to be more active than they are currently (Godin & Conner, 2008; Rhodes & Rebar, 2017). However, recent behavioural surveillance data suggests an overwhelming majority of North American adults (~80%) fail to meet these guideline based physical activity recommendations (Clarke, Norris & Schiller, 2017; Public Health Agency of Canada, 2016). These statistics, in concert with evidence suggesting people are motivated to become more active, highlight the need to develop a better understanding of factors that limit and facilitate translation of people's intentions into physical activity behaviour.

1.2 Overview of Self-regulation and Self-control

1.2.1 Self-Regulation

Self-regulation has received substantial attention over the past two decades. Self-regulation refers to the general process of altering one's thoughts, emotions and behaviours to pursue long-term standards or goals (Carver & Scheier, 2016). Self-control refers to situation-specific instances of self-regulation that require alteration of unwanted behavioural, emotional and cognitive responses to align with overarching standards or goals (Baumeister & Vohs, 2016). Baumeister, Schmeichel and Vohs (2007a) have suggested there are four fundamental components underlying self-regulation of behaviour. These key components include standards of a desired behaviour, motivation to meet these standards, monitoring situations and cognitions that may hinder behavioural attainment, and willpower to control urges that do not align with desired behaviour.

Self-control has been linked to a breadth of positive outcomes including career success, academic outcomes, and several important health behaviours including physical activity (Baumeister, Heatherton & Tice, 1994; de Ridder, Lensvelt-Mulders, Finkenauer, Stok, & Baumeister, 2012; Mischel, Cantor & Feldman, 1996). From this standpoint, self-control has been identified as a trait specific factor in that some people possess a greater ability to self-regulate behaviour towards long-term goals than others (Baumeister et al., 1994; Mischel et al., 1996; Tangney, Baumeister & Boone, 2004). Self-regulation is also situational, or state-specific, as people face several momentary circumstances throughout their day that can either strengthen or weaken their ability to enact self-control at any point in time (Baumeister, 2014; Baumeister et al., 1994; Baumeister, Vohs & Tice, 2007b).

1.2.2 Self-control

State-specific self-control has received a significant amount of attention over the past two decades with particular interest in the phenomenon of ego depletion. Ego depletion refers to an increased susceptibility to self-control failure due to prior engagement in a task requiring self-control (Baumeister et al., 2007b). Hundreds of studies across various domains have shown that performing an initial task requiring self-control leads to negative effects on subsequent tasks requiring self-control over cognitive, emotional or behavioural responses (cf. Friese, Loschelder, Gieseler, Frankenbach & Inzlicht, 2018).

An early meta-analysis of the self-control literature revealed a medium sized negative carryover effect of previous self-control exertion, or ego depletion ($d = .62$; Hagger, Wood, Stiff & Chatzisarantis, 2010). However, there has been considerable controversy regarding the magnitude of the ego depletion effect. Specifically, additional meta-analysis using alternative techniques (Carter, Kofler, Forster, & McCullough, 2015) and a registered replication project (Hagger et al., 2016) have failed to show a statistically-significant ego depletion effect.

Although critical concerns were raised by this research, other researchers were quick to respond to this evidence by pointing out limitations to the procedures and techniques used by these studies. For instance, criticisms were raised about Carter and colleagues (2015) "loose" inclusion criteria that appeared to ignore any quality standards for studies as well as inappropriate use of precision-effect test and precision-effect estimate with standard errors techniques (Cunningham & Baumeister, 2016; Dang, 2017). Concerns were also raised about the replication project as Hagger et al.'s ego depletion manipulation was shown to have been ineffective insofar as it did not elicit scores beyond the midpoint of the scale for three out of four of the self-reported measures used to quantify whether the task was "depleting"(Baumeister, Tice & Vohs, 2018; Dang, 2016). In fact, re-analysis of Hagger's data found that among participants who reported the self-control depletion manipulation was effortful demonstrated reduced subsequent self-control (Dang, 2016).

Despite these specific criticisms, controversy continues in this area of the literature as a recent analysis of the self-control literature suggests the effects reported by Hagger et al. (2010) may be an overestimation of the magnitude of the ego depletion effect and that it is more likely ego depletion confers a small to medium sized effect on subsequent task performance (g = .38; Dang, 2017). Overall, prior self-control exertion generally reduces one's ability to restrain subsequent unwanted urges or responses. However, some attention has begun to focus on the effort-based demands of the tasks people engage in, which may be a crucial factor influencing the ego depletion effect.

1.2.3 The Role of Effort in Self-control

Effort has been defined as the intensity of mental and/or physical work applied toward an outcome (Eisenberger, 1992). Hagger and colleagues (2010) meta-analysis revealed that engaging in tasks that require self-control is associated with a significant medium sized effect (*d* = .64) on perceived effort. Effort often corresponds with the difficulty of a task and is associated with task aversion (Dreisbach & Fischer, 2015; Kurzban, 2016; Saunders, Lin, Milyavskaya & Inzlicht, 2016). The underlying cognitive processes involved in effort regulation provide insight in terms of why people avoid tasks that are effortful or struggle to exert effort when performing tasks for prolonged periods despite potential benefits that may result from performance.

1.3 Overview of Fatigue

1.3.1 What is Fatigue?

Fatigue is defined as a disabling symptom in which physical and cognitive function is limited by the interaction between physiological and psychological factors (Enoka & Duchateau, 2016). Aside from phenomenological experiences, reduced task performance is the most salient characteristic of fatigue. Performance impairments have been documented across a variety of outcome measures indicative of physical and mental fatigue including, but not limited to speed, accuracy, force and productivity (e.g., Boksem, Meijman & Lorist, 2006; Bray, Martin Ginis, Hicks & Woodgate, 2008; Lorist, Boksem & Ridderinkhof, 2005; Ricci, Chee, Lorandeau & Berger, 2007; Rozand, Lebon, Papaxanthis & Lepers, 2015).

From a healthcare perspective, fatigue is unlike many symptoms that have specific tests or biomarkers for assessment, as it only measureable via self-report. Chronic fatigue is defined as excessive fatigue that arises from unknown causes (Shephard, 2001) and is reported in more than 20% of patients diagnosed with neurological and psychiatric disorders, making it one of the most prevalent symptoms of those disorders (Adams, Victor & Ropper, 1997). Population-based research has identified milder forms of fatigue affect roughly 20% of people on a daily basis (Aritake et al., 2015; Chen, 1986; Junghaenel, Christodoulou, Lai & Stone, 2011; Lerdal, Wahl, Rustoen, Hanestad & Moum, 2005; Loge, Ekeberg & Kaasa, 1998). Evidence suggests fatigue may be much more prevalent among certain healthy populations. Specifically, data indicates roughly half of post-secondary students (American College Health Association, 2015) and the adult workforce complain of symptoms of fatigue daily (Ricci et al., 2007). Although a myriad of factors may contribute to the high prevalence of fatigue, many day-to-day school and workplace tasks require high levels of mental effort, which could cause these symptoms to appear.

Exerting effort performing either a physical or cognitive task can lead to similar subjective experiences of fatigue (Krupp, LaRocca, Muir-Nash & Steinberg, 1989). Interestingly, it appears that fatigue sensations stemming from tasks requiring effortful mental and physical self-regulation can cross over from one task to another. For example, people who experience fatigue when performing a cognitive task may be quicker to fatigue when they begin to perform a physical task, which suggests mental and physical fatigue, are represented by overlapping systems (Evans, Boggero & Segerstrom, 2016).

1.3.2 Mental Fatigue

Fatigue that manifests as a result of performing tasks requiring effortful cognitive demands or cognitive control is referred to as mental fatigue (Boksem & Tops, 2008). Mental fatigue is complex psychophysiological phenomenon that results in feelings of tiredness, lack of energy, or boredom (Hockey, 2013). A body of research has shown that exposure to effortful cognitive control tasks meant to induce mental fatigue results in subsequent cognitive and behavioural performance impairments (e.g., Boksem et al., 2006; Lorist et al., 2005; McMorris, Barwood, Hale, Dicks & Corbett, 2018; Van Cutsem, Marcora, De Pauw, Bailey, Meeusen & Roelands, 2017)

In order to induce mental fatigue, researchers have developed manipulations that involve cognitive functions and typically vary in terms of two task parameters; the duration spent performing a task and the difficulty of the task. Both procedures have been shown to successfully induce symptoms of mental fatigue objectively and subjectively. Objectively, mental fatigue is characterized in terms of decreased response speed and/or accuracy while performing the task (Boksem, Meijman & Lorist, 2005, 2006). In contrast, mental fatigue is characterized subjectively by increased feelings or perceptions of fatigue, which are quantified using self-report measures such as Visual Analogue Scales (Wewers & Lowe, 1990). Although some researchers argue that mental fatigue is due to time on task effects (e.g., Van Cutsem et al., 2017), evidence suggests task difficulty can also result in rapid performance decrements and perceptions of fatigue in a fraction of the time required by less difficult tasks (Boksem & Tops, 2008; Mackworth, 1964; Warm et al., 2008). For example, cognitive tasks that are dependent upon executive functions (i.e., cognitive control) require high levels of cognitive resources and lead to greater fatigue than non-executive tasks (Hofmann, Schmeichel & Baddeley, 2012).

1.4 Merging Bodies of Literature

1.4.1 Linking Self-control and Mental Fatigue

One concept that appears to be central to both self-control and mental fatigue is cognitive control. Inzlicht, Bartholow and Hirsh (2015) define cognitive control as one form of self-control involving conscious cognitive processes that enable flexible goal-directed behaviour in the face of unwanted responses. The authors further explain that exerting cognitive control in order to self-regulate one's thoughts, emotions, or behaviour is perceived as effortful, and consistently leads to symptoms of mental fatigue. From this perspective, these two bodies of literature can be linked by conceptualizing self-control as the action of regulating behavioural processes, and mental fatigue as a symptomatic consequence of engaging in effortful self-control. Theorists in both the self-control and mental fatigue literatures have suggested symptoms of fatigue arise as a signaling mechanism. Baumeister and Vohs (2016) proposed that perceptions of fatigue signal declines in available energy to further self-regulate, whereas Boksem and

Tops (2008) posit that fatigue is a signal to alter one's behavioural strategy to involve less effort. Research examining brain regions involved in cognitive control exertion further supports the intersection among these streams of inquiry.

Research involving neurophysiological and neuroimaging measurement techniques demonstrate there are specific brain regions that are active during effortful control. For example, exerting self-control is associated with decreased activation in areas responsible for effortful control of goal-directed behaviour that include the anterior cingulate cortex and prefrontal cortex, two areas that exert top-down control on subcortical areas involved in emotion and reward (cf. Heatherton & Wagner, 2011). Similarly, a consistent body of research has shown that inducing mental fatigue though effortful cognitive exertion leads to reductions in activation among brain regions (i.e., dorsolateral prefrontal cortex, dorsal anterior cingulate cortex and anterior insula) known to play a fundamental role regulating effortful behaviour (cf. Müller & Apps, 2018).

The centrality of cognitive control among self-control and mental fatigue may be the key factor for linking this literature. Moreover, methodological design and manipulation selection also provides insight regarding the high degree of overlap. Studies from both fields commonly employ higher order cognitive tasks involving executive processes such as inhibition (e.g., Stroop task, flanker task, AX-Continuous Performance Test [AX-CPT]) to induce ego depletion or mental fatigue. As these tasks target similar neural pathways, it makes sense that we see significant overlap among brain regions involved. Both areas of research have also demonstrated these effects are not domain specific. For example, effortful cognitive control exertion does not only affect subsequent cognitive performance, but also negatively affects subsequent effortful physical control. This again illustrates the potential of a common set of underlying effort-based processes that govern these neurological alterations and downstream performance. In order to better understand and interpret these effects, strong theoretical frameworks are needed.

1.4.2 Theoretical Frameworks to Understand Mental Fatigue and Effort Regulation

As the body of literature examining self-control continues to grow, several different perspectives have been brought forth to better understand the nature and extent of these findings. These theories are generally rooted in resource based or motivational accounts. One of the most prominent theories of self-control is the strength model which was originally formulated by Baumeister, Tice and Heatherton (1996). The authors proposed that self-control is dependent on energetic resources which are depleted with effortful regulation, curtailing people's future ability to successfully enact self-control. Despite abundant research attempting to uncover a biologically-based "resource" (e.g., Gailliot & Baumeister, 2007), the origin as well as methods to measure or operationalize the state of the resource remain unknown. This lack of evidence has led to considerable criticism within the literature and to alternative theorizing that self-control is not dependent upon a resource, but on motivation and a reasoned assessment of benefits and costs of one's response alternatives (Inzlicht & Schmeichel, 2012; Kotabe & Hofmann, 2015; Kurzban, Duckworth, Kable & Myers, 2013). Motivational theories of self-control suggest that prolonged exertion of effortful control eventually leads individuals to withdraw effort and engage in more leisurely pursuits that do not require further effortful control (Inzlicht & Schmeichel, 2016; Inzlicht, Schmeichel & Macrae, 2014). Baumeister and Vohs (2016) have since revisited the strength model to merge these perspectives, updating predictions based on more recent data to suggest increased motivation may allow individuals to access resources that are otherwise kept in reserve.

Recent theorizing and empirical evidence provides support for this motivational account of self-control in the face of fatigue. Based on neurological imaging evidence, Müller and Apps (2018) have hypothesized that brain regions responsible for effortful control monitor levels of fatigue and relay input to systems responsible for deciding to continue investing effort when the benefits no longer outweigh the effortful costs required to further self-regulate behaviour. Although their interpretation of the evidence did not specifically refer to physical activity, given that engaging in physical activity requires effort regulation which may be influenced by mental fatigue, motivation-based frameworks provide a sound basis for interpreting the existing results and uncovering additional processes which may underlie the mental fatigue – physical performance relationship.

1.5 Mental Fatigue and Physical Activity Behaviour

Over the past decade there has been an evolving interest in the topic of fatigue as it relates to physical performance (e.g., Enoka & DuChateau, 2016; Noakes, St. Clair Gibson & Lambert, 2005), however research examining the relationship between fatigue and physical activity from an epidemiological or public health perspective has received limited attention. Instead, lab-based research aiming to understand the influence of mental fatigue on physical performance has become an emerging area of study.

Several reviews and meta-analyses amalgamating the growing body of literature examining the relationship between mental fatigue and physical performance have been published in the last three years. In each case, the evidence has consistently shown mental fatigue impairs subsequent performance across a wide range of physical tasks (cf., Englert, 2016; McMorris et al., 2018; Van Cutsem et al., 2017). For example, negative effects of mental fatigue have been witnessed for aerobic exercise performance on time to exhaustion tests as well as time trial performance for cycling and running (e.g., MacMahon, Schücker, Hagemann & Strauss, 2014; Marcora, Staiano & Manning, 2009). Performance of different resistance exercise tasks are also impaired by mental fatigue including isometric endurance (e.g., Bray et al., 2008; Graham & Bray, 2015), localized contractions of leg muscles (e.g., Pageaux, Marcora & Lepers, 2013), and whole-body work outs (e.g., Graham, Martin Ginis & Bray, 2017; Head et al., 2016). These effects also extend to VO_{2max} testing (Zering, Brown, Graham & Bray, 2016), and across a variety of sport-specific tasks such as performing soccer drills (e.g., Smith et al., 2016). Clearly, the negative carryover effects of mental fatigue have an extensive breadth, however there are several questions relating to the mechanisms mediating these effects that remained unanswered.

1.5.1 Gaps and Limitations of Research on Mental Fatigue and Physical Performance

Studies examining the association between mental fatigue and physical performance have been informative in terms of establishing the reliability of this phenomenon and determining the magnitude and direction of the effects. However, despite some efforts at investigating potential underlying physiological and psychological mechanisms that could explain why the effects occur, there remain a myriad of unanswered questions. Among these many questions, four areas have received limitation attention to date and are the focus of this dissertation. These issues relate to a lack of attention regarding potential dose-response effects, underlying psychological mechanisms, generalizability of the types of physical tasks and samples used to date, and lastly, intervention strategies to counter the deleterious effects of mental fatigue on physical performance.

1.5.2 Does a Dose-Response Relationship Exist?

To date, results from studies examining the relationship between mental fatigue and physical performance have demonstrated a wide range of effects. Some studies have revealed null effects (e.g., Schücker & MacMahon, 2016), while others have demonstrated extremely large effects (e.g., Graham et al., 2017).

These discrepancies may be due largely to differences in methodological designs involving a variety of cognitive control tasks with varying difficulties and durations of exposure as well as different physical tasks; some of which require sustained sub-maximal exertion over time and others that involve brief maximal exertion. For instance, studies represented in the mental fatigue – physical performance literature have utilized cognitive tasks requiring inhibitory processes such as the AX-CPT and Stroop task and had participants perform those tasks for at least 30 minutes continuously (e.g., Marcora et al., 2009; Pageaux, Marcora, Rozand & Lepers, 2015; Smith, Marcora, & Coutts, 2015). In contrast, studies in the self-control literature have employed the same, or similar cognitive control tasks (e.g., Stroop task, text transcription task) involving inhibitory processes for durations lasting 5 minutes or less (e.g., Bray et al., 2008; Graham & Bray, 2015). Despite these dissimilarities in task duration, these separate lines of inquiry have shown similar impairments in physical performance across a range of tasks. However, these effects are drawn from designs that have involved simple contrasts between the mentally-fatiguing or self-control-depleting cognitive control task and a non-fatiguing, or less fatiguing control task. Thus, a major shortcoming of these studies is that they limit understanding to an all-or-nothing effect and leaves a gap in our knowledge as to the nature of the dose-response effect.

Within the self-control literature, there have been recent calls for studies investigating a dose-response relationship between cognitive control exertion and subsequent task performance (Lee, Chatzisarantis & Hagger, 2016). In the only study to have used graded doses of a self-control manipulation, vanDellen, Hoyle and Miller (2012) found evidence of a threshold effect when people performed consecutive cognitive tasks requiring self-control. However, studies employing similar paradigms designed to test dose-response effects among the mental fatigue – physical performance relationship have not been conducted. Fixing the difficulty by selecting one experimental manipulation and manipulating the time-on-task would help to answer questions of: at what point does mental fatigue lead to negative carryover effects on physical performance and whether further increases in mental fatigue leads to further reductions in performance?

1.5.3 Psychological Factors Underlying the Mental Fatigue – Physical Performance Relationship

To date, research examining the effects of mental fatigue or self-control exertion on physical performance has been divided into two fields. Looking at the journals these studies have been published in, it is clear the majority of studies investigating mental fatigue have taken a physiological approach (e.g., *European Journal of Physiology; Journal of Applied Physiology*), whereas studies investigating self-control exertion/depletion have taken a psychological approach (e.g., *Journal of Sport and Exercise Psychology; Sport, Exercise and Performance Psychology*). Although outside of the scope of this dissertation, research investigating potential physiological mechanisms (e.g., muscle activation, blood lactate) underlying the mental fatigue – physical performance relationship has produced evidence that muscle activation may be impaired by mental fatigue. Conversely, there still remain a number of gaps among the psychological literature that need to be addressed in order to better understand the downstream negative effects that perceptions of mental fatigue impart on physical performance.

The mechanistic processes outlined among several theoretical models of self-control have led many empirical studies to examine constructs such as motivational and emotional states. In fact, motivation has received the most attention among psychological variables to date. Despite persuasive theoretical accounts, studies have failed to show changes in self-reported measures of task and intrinsic motivation following exposure to an effortful cognitive control task (MacMahon et al., 2014; Marcora et al., 2009; Pageaux et al., 2013; Pageaux, Lepers, Dietz & Marcora, 2014; Schücker & MacMahon, 2016). This evidence would suggest a lack of a role of motivation, however, there has been evidence that experimental manipulations designed to affect motivation (e.g., offering rewards) can counteract self-control depletion (Luethi et al., 2016; Muraven & Slessareva, 2003). Therefore, it may be that self-report measures of motivation do not effectively assess changes in motivation that may occur. Researchers have called for more research using measures that may capture proximal shifts in motivation that may be due to cognitive control exertion (Jia & Hirt, 2016).

One example of a measure that may capture momentary shifts in motivation is the amount of effort people plan to invest in performing the task. Using this measure of motivation, Martin Ginis and Bray (2010) showed that exposure to a brief incongruent Stroop task caused people to reduce the intensity at which they intended to exercise compared to a control condition. From an operationalization standpoint, this measure captures both the direction and the intensity of action (Atkinson, 1957). However, because Martin Ginis and Bray (2010) did not investigate whether changes in intended exercise intensity corresponded with changes in exercise performance, questions remain as to whether these subtle changes in intentions could explain the reductions in physical performance that are commonly seen in the self-control depletion literature. Considering the centrality of motivation within many theories and the limited scope with which motivation has been assessed, it seems premature to dismiss the role of motivation and worthwhile to address this gap in the literature by exploring a broad array of motivational variables to better evaluate potential mechanistic processes involved in the mental fatigue – physical performance relationship.

In addition to measures that directly attempt to assess motivation, another construct associated with motivation is self-efficacy. Self-efficacy refers to people's perceptions of their abilities to perform specific tasks (Bandura, 1997). Studies have shown that exposure to an effortful cognitive control task leads to temporary reductions in people's self-efficacy to perform a physical performance task (Graham & Bray, 2015; Graham et al., 2017). Results from these initial studies also showed that task self-efficacy partially mediates the relationship between effortful cognitive control exertion and subsequent isometric handgrip endurance. Graham et al., (2017) built on these findings drawing from Bandura's (1997) theorizing about physiological and emotional states affecting self-efficacy and investigating the mediating roles of fatigue and self-efficacy on subsequent task performance. Using a serial mediation model, Graham et al. (2017) showed that cognitive control exertion increases perceived fatigue, which in turn reduces self-efficacy, and leads to decreased resistance exercise performance. Together, evidence from these studies suggests self-efficacy may be an influential motivational perception that can be affected by mental fatigue that may be influential for physical performance. However, further research is needed to better understand this relationship.

As noted above, self-control theories (e.g., process model) have also proposed emotion is a major factor that can influence effortful control. Consistent with these perspectives, several studies have revealed that exposure to an effortful cognitive control task not only intensifies perceptions of mental fatigue, but also reduces affective valence (Dreisbach & Fischer, 2012; MacMahon et al., 2014; Marcora et al., 2009). As mentioned previously, research has statistically evaluated the mediating role of perceived fatigue on physical performance (Graham et al., 2017), however, the potential mediating effect of affective valence on the mental fatigue - physical performance relationship has not been investigated. Given that negative changes in mood states have been linked to physical performance impairments in previous studies (e.g., Marcora et al., 2009), the potential mediating role of affective valence should be examined. Overall, given numerous psychological variables have been identified as potential mediators of the mental fatigue – physical performance relationship, there should be a focused effort on future research to evaluate mediating variables that could help explain how mental fatigue affects physical performance.

1.5.4 Ecological Validity of the Mental Fatigue – Physical Activity Literature

While a growing body of research consistently demonstrates mental fatigue is a factor that impacts subsequent physical performance, current evidence lacks generalizability to the general population for at least two reasons. First, the majority of findings are derived from samples consisting of active individuals or trained athletes (e.g. Marcora et al., 2009; MacMahon et al., 2014). Given the majority of the populations of industrialized countries are inactive or active at levels below minimal recommendations (Clarke, Norris & Schiller, 2017; Public Health Agency of Canada, 2016) current evidence may not be applicable to understanding physical activity in the population. Given their lack of exposure to physical activity, inactive or insufficiently active individuals may be more susceptible to performance decrements when fatigued compared to people that have gained experience self-regulating physically effortful behaviour.

The second reason is that although some studies have investigated samples that are more representative of the general population, physical performance in those studies has been assessed using specific tasks such as submaximal isometric handgrip endurance (e.g., Bray et al., 2008; Graham & Bray, 2015). These exercise modalities are common to some activities of daily living such as carrying groceries, but do not reflect the types of physical activities people commonly engage in for fitness and health benefits. Consequently, there is a disconnect between exercise tasks and samples of participants to evaluate performance of those tasks that limits the external validity of the majority of studies investigating the effects of mental fatigue on exercise performance.

Moving forward, it is imperative that research examines the extent to which mental fatigue may affect the types of physical activities recommended by public health guidelines that the general population engages in for health benefits. Determining the impact of mental fatigue on adherence to guideline based physical activity may help explain why the majority of the population accrues insufficient levels of MVPA despite being aware of the importance of being physically active and having intentions to be more active than they currently are.

1.5.5 Intervention Strategies to Overcome Mental Fatigue

While many opportunities exist to explore potential mediating mechanisms that can account for the effects of mental fatigue on physical performance, there is also a need to investigate personal and situational factors that may alter the magnitude or direction of the mental fatigue - performance relationship. One area that has received limited attention is the examination of intervention strategies that may be effective to overcome mental fatigue. Discovering effective intervention strategies is important for understanding factors that may affect physical performance, but also has broader potential to apply to situations that could help optimize the health associated benefits of exercise among individuals experiencing fatigue as a barrier to being physically active.

To date, only two studies have investigated intervention strategies aiming to counter the typical negative carryover effects associated with mental fatigue. Taking a motivational approach, Graham, Bray & Martin Ginis (2014) demonstrated that providing autonomy supportive feedback was able to restore isometric handgrip endurance performance following exposure to a 5-minute Stroop task. In another study, Azevedo, Silva-Cavalcante, Gualano, Lima-Silva & Bertuzzi (2016) tested whether caffeine, a pharmacological stimulant known to attenuate effects of mental fatigue could restore physical performance. The authors demonstrated that caffeine not only restored performance following exposure to a mentally fatiguing 90-minute AX-CPT, but led to performance levels over and above that witnessed in the control condition. These results indicate the effects of mental fatigue can be countered and opens the door for further inquiry to determine the efficacy of other motivational and self-regulatory factors that have been shown to facilitate behavioural control.

As previously mentioned, motivation is one of the four key components of self-regulation (Baumeister et al., 2007a) and has been identified as a major factor among several recent theoretical accounts (Baumeister & Vohs, 2016; Botvinick & Braver, 2015; Inzlicht & Schmeichel, 2012). Results from the self-control literature have consistently shown that manipulations aiming to improve motivation can successfully attenuate ego depletion effects. Specifically, targeting motivational processes through providing autonomy and performance contingent incentives have been proven to be efficacious for restoring self-control (Legault & Inzlicht, 2013; Luethi et al. 2016; Moller, Deci & Ryan, 2006; Muraven & Slessareva, 2003). Although Graham et al. (2014) have extended this line of research to physical self-regulation by investigating autonomy-based motivational manipulations, additional strategies such as offering incentives have not been examined. Incentives have been proven to increase physical activity adherence as evidenced by an 11.55% increase reported by a recent meta-analysis (Mitchell et al., 2013), however, the effect of incentives on physical performance has not been tested among mentally fatigued individuals. Thus, improving our understanding of the role of incentives for motivating physical activity behaviour when mentally-fatigued may have implications for improving guideline based PA adherence among individuals that experience symptoms of fatigue on a daily basis.

Research examining interventions targeting additional key self-regulatory factors also deserves attention. One prominent theory of self-regulation is control theory (Carver & Scheier, 1982, 2016). According to control theory (Carver & Scheier, 1982, 2016), behavioural regulation is enabled through a negative feedback loop of cybernetic control driven by the interaction of four factors: one's current behaviour, having a standard/goal, monitoring behavioural feedback towards that goal, and adjusting behaviour to minimize the discrepancy between one's current state and desired goal. Research has shown behavioural monitoring can attenuate negative carryover effects from one cognitively-demanding self-control task to another (Voce, & Moston, 2016; Wan & Sternthal, 2008). Moreover, a recent meta-analysis of field-based physical activity trials showed that monitoring behavioural feedback towards physical activity goals is a highly effective intervention technique for increasing physical activity (d = 1.98; Harkin et al., 2016). To this point, the goal-directed feedback loop proposed by control theory has not been evaluated as a process to counter the negative effects of mental fatigue on exercise performance. Investigating the effects of behavioural monitoring in combination with physical activity goals/standards is a potentially promising strategy to improve exercise performance or adherence given the popularity of individualized behavioural monitoring tools (e.g., heart rate monitors, activity trackers) (Macridis, Johnston, Johnson & Vallance, 2018).

1.6 Objectives and Hypotheses

1.6.1 General Purpose of Dissertation

The overarching objective of this dissertation was to investigate the association between mental fatigue and physical activity behaviour and systematically examine potential mediators and moderators of the mental fatigue - physical performance relationship.

1.6.2 Specific Objectives

The specific objectives of the studies in this dissertation are to:

1) Investigate whether a dose-response relationship exists between mental fatigue and physical performance, while also examining psychological processes that may mediate this relationship.

2) Examine whether offering a motivational monetary incentive attenuates the negative effects of mental fatigue on physical performance
3) Investigate the effects of mental fatigue on performance of exercise reflective of current physical activity guidelines in a sample of insufficiently active participants and examine how mental fatigue affects motivational perceptions towards engaging in physical activity
4) Examine heart rate biofeedback as a potential moderator of the effects of effortful cognitive control exertion on vigorous-intensity exercise reflective of current public health physical activity guidelines and to investigate the effects of mental fatigue on measures of motivation specifically related to physical activity performance.

1.6.3 Specific Hypotheses

The specific hypotheses of the studies within this dissertation were that:

1) Incremental increases in exposure to a mentally fatiguing cognitive control task would lead to incremental increases in mental fatigue and incremental decreases in affective valence, motivation and task self-efficacy which would correspond with incremental decreases in subsequent physical endurance performance in a linear dose-response manner, thus mediating the relationship between mental fatigue and physical performance.
2) Exposure to a mentally fatiguing cognitive control task would result in subsequent physical performance decrements compared with a non-fatiguing cognitive control task and that providing a monetary incentive

would attenuate performance decrements when fatigued and restore performance to levels achieved when provided an incentive in a non-fatigued state

3) Engaging in a mentally fatiguing cognitive control task would reduce intended physical exertion for an upcoming bout of exercise and decrease the amount of total work performed during that 30-minute self-paced exercise session in comparison to a non-fatiguing task requiring low cognitive control exertion.
4) Compared to a non-fatiguing control task, performing a mentally fatiguing cognitive control task would lead to lower levels of intended exercise intensity and decreased commitment to vigorous-intensity exercise goals, which in turn would result in performing less work while exercising at a lower intensity during a 20-minute bout of self-paced vigorous exercise. It was further predicted that when compared to being mentally-fatigued, receiving heart rate biofeedback would restore performance to intensities and workloads accomplished when not mentally-fatigued.

1.7 Summary

Four laboratory-based experiments were conducted to test dose-response effects (Study 1), examine influential underlying psychological variables (Studies 1, 3 and 4), expand generalizability (Studies 3-4), and test the efficacy of intervention strategies (Studies 2 and 4) among the mental fatigue – physical activity performance relationship. Each of these four studies is presented in detail over the following four chapters followed by a general discussion which summarizes findings and how this work contributes to the mental fatigue – physical activity performance literature while also highlighting theoretical and practical implications.

References

Adams, R. D., Victor, M., & Ropper, A. H. (1997). Fatigue, asthenia, anxiety and depressive reactions. In R. D. Adams, M. Victor & A H. Ropper (6 ed.), *Principles of Neurology (pp.* 497-507). New York, NY: McGraw Hill.

American College Health Association (2015). *American College Health Association - national college health assessment II: Undergraduate students reference group data report spring 2015*. Hanover, MD: American College Health Association.

Aritake, S., Kaneita, Y., Ohtsu, T., Uchiyama, M., Mishima, K., Akashiba, T., ... & Ohida, T. (2015). Prevalence of fatigue symptoms and correlations in the general adult population. *Sleep and Biological Rhythms, 13*, 146-154. doi:10.1111/sbr.12099

Atkinson, J. W. (1957). Motivational determinants of risk-taking behavior. *Psychological Review, 64*, 359-372. doi:10.1037/14156-004

Azevedo, R., Silva-Cavalcante, M. D., Gualano, B., Lima-Silva, A. E., & Bertuzzi, R. (2016). Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. *European Journal of Applied Physiology*, *116*, 2293-2303. doi:10.1007/s00421-016-3483-y

Bandura, A. (1997). *Self-efficacy: The exercise of control*. New York, NY: Freeman.

Baumeister, R.F. (2014). Self-regulation, ego depletion, and inhibition. *Neuropsychologia, 65*, 313–319. doi:10.1016/j.neuropsychologia.2014.08.012

Baumeister, R. F., Heatherton, T. F., & Tice, D. M. (1994). *Losing control: How and why people fail at self-regulation*. San Diego, CA: Academic Press.

Baumeister, R. F., Schmeichel, B. J., & Vohs, K. D. (2007a). Self-regulation and the executive function: The self as controlling agent. In A. W. Kruglanski & E. T. Higgins (Eds.), *Social psychology: Handbook of basic principles* (pp. 516-539). New York, NY, US: Guilford Press.

Baumeister, R. F., Tice, D. M., & Vohs, K. D. (2018). The strength model of self-regulation: Conclusions from the second decade of willpower research. *Perspectives on Psychological Science*, *13*, 141-145. doi:10.1177/1745691617716946

Baumeister, R. F., & Vohs, K. D. (2016). Strength model of self-regulation as limited resource: Assessment, controversies, update. *Advances in Experimental Social Psychology, 54*, 67-127. doi:10.1016/bs.aesp.2016.04.001

Baumeister, R.F., Vohs, K.D., & Tice, D.M. (2007b). The strength model of self-control. Current *Directions in Psychological Science, 16*, 351–355. doi:10.1111/j.1467-8721.2007.00534.x

Biddle, S. J., & Asare, M. (2011). Physical activity and mental health in children and adolescents: a review of reviews. *British Journal of Sports Medicine, 45*, 886-895. doi:10.1136/bjsports-2011-090185

Bherer, L., Erickson, K. I., & Liu-Ambrose, T. (2013). A review of the effects of physical activity and exercise on cognitive and brain functions in older adults. *Journal of Aging Research*, *2013*, 657508. doi:10.1155/2013/657508

Boksem, M. A., Meijman, T. F., & Lorist, M. M. (2005). Effects of mental fatigue on attention: an ERP study. *Cognitive Brain Research, 25,* 107-116. doi:10.1016/j.cogbrainres.2005.04.011

Boksem, M. A., Meijman, T. F., & Lorist, M. M. (2006). Mental fatigue, motivation and action monitoring. *Biological Psychology, 72,* 123-132. doi:10.1016/j.biopsycho.2005.08.007

Boksem, M. A., & Tops, M. (2008). Mental fatigue: costs and benefits. *Brain Research Reviews, 59,* 125-139. doi:10.1016/j.brainresrev.2008.07.001

Botvinick, M., & Braver, T. (2015). Motivation and cognitive control: From behavior to neural mechanism. *Annual Review of Psychology, 66*, 83–116. doi:10.1146/annurev-psych-010814-015044

Bray, S.R., Martin Ginis, K.A., Hicks, A.L., & Woodgate, J. (2008). Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology,45*, 337–343. doi:10.1111/j.1469-8986.2007.00625.x

Cadore, E. L., Rodríguez-Mañas, L., Sinclair, A., & Izquierdo, M. (2013). Effects of different exercise interventions on risk of falls, gait ability, and balance in physically frail older adults: a systematic review. *Rejuvenation Research*, *16*, 105-114. doi:10.1089/rej.2012.1397

Carter, E.C., Kofler, L.M., Forster, D.E., & McCullough, M.E. (2015). A series of meta-analytic tests of the depletion effect: Self-control does not seem to rely on a limited resource. *Journal of Experimental Psychology: General, 144*, 796–815. doi:10.1037/xge0000083

Carver, C. S., & Scheier, M. F. (1982). Control theory: A useful conceptual framework for personality–social, clinical, and health psychology. *Psychological Bulletin, 92*, 111-135. doi:10.1037/0033-2909.92.1.111

Carver, C. S., & Scheier, M. F. (2016). Self-regulation of action and affect. In K. D. Vohs & R. F Baumeister (3rd ed.), *Handbook of self-regulation: Research, theory, and applications* (pp. 3-23). New York, NY: Guilford Press.

Chang, Y. K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: a meta-analysis. *Brain Research*, *1453*, 87-101. doi:10.1016/j.brainres.2012.02.068

Chen, M. K. (1986). The epidemiology of self-perceived fatigue among adults. *Preventive Medicine*, *15*, 74-81. doi:10.1016/0091-7435(86)90037-x

Clarke, T. C., Norris, T., & Schiller, J. S. (2017). Early release of selected estimates based on data from 2016 National Health Interview Survey. *National Center for Health Statistics.*

Cunningham, M.R., & Baumeister, R.F. (2016). How to make nothing out of something: Analyses of the impact of study sampling and statistical interpretation in misleading metaanalytic conclusions. *Frontiers in Psychology*, *7*, 1639. doi:10.3389/fpsyg.2014.00823

Dang, J. (2016). Commentary: A multilab preregistered replication of the ego depletion effect. *Frontiers in Psychology*, *7*, 1155. doi:10.3389/fpsyg.2016.01155

Dang, J. (2017). An updated meta-analysis of the ego depletion effect. *Psychological Research*, *4*, 645-651. doi: 10.1007/s00426-017-0862-x

de Ridder, D.T., Lensvelt-Mulders, G., Finkenauer, C., Stok, F.M., & Baumeister, R.F. (2012). Taking stock of self-control: A meta-analysis of how trait self-control relates to a wide range of behaviors. *Personality and Social Psychology Review*, *16*, 76–99. doi:10.1177/ 1088868311418749

Dreisbach, G., & Fischer, R. (2015). Conflicts as aversive signals for control adaptation. *Current Directions in Psychological Science*, *24*, 255-260. doi:10.1177/0963721415569569

Eisenberger, R. (1992) Learned industriousness. *Psychological. Review*. *99*, 248–267. doi:10.1037//0033-295x.99.2.248

Englert, C. (2016). The strength model of self-control in sport and exercise psychology. *Frontiers in Psychology*, *7*, 314. doi:10.3389/fpsyg.2016.00314

Enoka, R. M., & Duchateau, J. (2016). Translating fatigue to human performance. *Medicine and Science in Sports and Exercise*, *48*, 2228-2238. doi:10.1249/MSS.0000000000000929

Evans, D. R., Boggero, I. A., & Segerstrom, S. C. (2016). The nature of self-regulatory fatigue and “ego depletion” lessons from physical fatigue. *Personality and Social Psychology Review*, *20*, 291-310. doi:10.1177/1088868315597841

Friese, M., Loschelder, D. D., Gieseler, K., Frankenbach, J., & Inzlicht, M. (2018). Is ego depletion real? An analysis of arguments. *Personality and Social Psychology Review*. Advance online publication. doi: 10.1177/1088868318762

Garber, C. E., Blissmer, B., Deschenes, M. R., Franklin, B. A., Lamonte, M. J., Lee, I. M., ... & Swain, D. P. (2011). American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. *Medicine & Science in Sports & Exercise*, *43*, 1334-1359. doi:10.1249/MSS.0b013e318213fefb

Gailliot, M. T., & Baumeister, R. F. (2007). The physiology of willpower: Linking blood glucose to self-control. *Personality and Social Psychology Review*, *11*, 303-327. doi: 10.1177/1088868307303030

Godin, G., & Conner, M. (2008). Intention-behavior relationship based on epidemiologic indices: anapplication to physical activity. *American Journal of Health Promotion, 22*, 180-182. doi:10.4278/ajhp.22.3.180

Graham, J. D., & Bray, S. R. (2015). Self-control strength depletion reduces self-efficacy and impairs exercise performance. *Journal of Sport and Exercise Psychology*, *37*, 477-488. doi:10.1123/jsep.2015-0064

Graham, J.D., Bray, S.R., & Martin Ginis, K.A. (2014). “Pay the piper”: It helps initially, but motivation takes a toll on self-control. *Psychology of Sport and Exercise, 15*, 89–96. doi:10.1016/j.psychsport.2013.09.007

Graham, J. D., Martin Ginis, K. A., & Bray, S. R. (2017). Exertion of self-control increases fatigue, reduces task self-efficacy, and impairs performance of resistance exercise. *Sport, Exercise, and Performance Psychology, 6,* 70-88. doi:10.1037/spy0000074

Hagger,M.S., Chatzisarantis, N.L., Alberts, H., Anggono, C.O., Batailler, C., Birt, A.R., …& Calvillo, D.P. (2016). A multi-lab preregistered replication of the ego depletion effect. *Perspectives on Psychological Science, 11*, 546–573. doi:10.1177/1745691616652873

Hagger, M.S., Wood, C., Stiff, C., & Chatzisarantis, N.L. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin, 136*, 495–525. doi:10.1037/a0019486

Harkin, B., Webb, T. L., Chang, B. P., Prestwich, A., Conner, M., Kellar, I., ... & Sheeran, P. (2016). Does monitoring goal progress promote goal attainment? A meta-analysis of the experimental evidence. *Psychological Bulletin, 142*, 198-229. doi:10.1037/bul0000025

Haskell, W. L., Lee, I. M., Pate, R. R., Powell, K. E., Blair, S. N., Franklin, B. A., ... & Bauman, A. (2007). Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Circulation, 116,* 1081-1093. doi:10.1161/circulationaha.107.185649

Head, J. R., Tenan, M. S., Tweedell, A. J., Price, T. F., LaFiandra, M. E., & Helton, W. S. (2016). Cognitive fatigue influences time-on-task during bodyweight resistance training exercise. *Frontiers in Physiology, 7,* 373. doi:10.3389/fphys.2016.00373

Heatherton, T. F., & Wagner, D. D. (2011). Cognitive neuroscience of self-regulation failure. *Trends in Cognitive Sciences, 15,* 132-139. doi:10.1016/j.tics.2010.12.005

Hockey, R. (2013). *The psychology of fatigue: Work, effort and control*. New York, NY: Cambridge University Press. doi:10.1017/CBO9781139015394

Hofmann, W., Schmeichel, B. J., & Baddeley, A. D. (2012). Executive functions and self-regulation. *Trends in Cognitive Sciences, 16,* 174-180. doi:10.1016/j.tics.2012.01.006

Inzlicht, M., Bartholow, B. D., & Hirsh, J. B. (2015). Emotional foundations of cognitive control. *Trends in Cognitive Sciences*, *19*, 126-132. doi:10.1016/j.tics.2015.01.004

Inzlicht, M., & Schmeichel, B. J. (2012). What is ego depletion? Toward a mechanistic revision of the resource model of self-control. *Perspectives on Psychological Science*, *7*, 450-463. doi:10.1177/1745691612454134

Inzlicht, M., & Schmeichel, B. J. (2016). Beyond limited resources: Self-control failure as the product of shifting priorities. In K. D. Vohs & R. F Baumeister (3rd ed.), *Handbook of self-regulation: Research, theory, and applications* (pp. 165-181). New York, NY: Guilford Press.

Inzlicht, M., Schmeichel, B. J., & Macrae, C. N. (2014). Why self-control seems (but may not be) limited. *Trends in Cognitive Sciences*, *18*, 127-133. doi:10.1016/j.tics.2013.12.009

Jia, L., & Hirt, E. R. (2016). Depletion suspends the comparator mechanism in monitoring: The role of chronic self-consciousness in sequential self-regulation. *Journal of Personality and Social Psychology*, *111*, 284-300. doi:10.1037/pspp0000108

Junghaenel, D. U., Christodoulou, C., Lai, J. S., & Stone, A. A. (2011). Demographic correlates of fatigue in the US general population: results from the patient-reported outcomes measurement information system (PROMIS) initiative. *Journal of Psychosomatic Research*, *71*, 117-123. doi:10.1016/j.jpsychores.2011.04.007

Kotabe, H. P., & Hofmann, W. (2015). On integrating the components of self-control. *Perspectives on Psychological Science, 10*, 618-638. doi:10.1177/1745691615593382

Krupp, L. B., LaRocca, N. G., Muir-Nash, J., & Steinberg, A. D. (1989). The fatigue severity scale: application to patients with multiple sclerosis and systemic lupus erythematosus. *Archives of Neurology, 46*, 1121-1123. doi:10.1001/archneur.1989.00520460115022

Kurzban, R. (2016). The sense of effort. *Current Opinion in Psychology*, *7*, 67-70. doi:10.1016/j.copsyc.2015.08.003

Kurzban, R., Duckworth, A., Kable, J. W., & Myers, J. (2013). An opportunity cost model of subjective effort and task performance. *Behavioral and Brain Sciences*, *36*, 661-679. doi:10.1017/s0140525x12003196

Lawlor, D. A., & Hopker, S. W. (2001). The effectiveness of exercise as an intervention in the management of depression: systematic review and meta-regression analysis of randomised controlled trials. *BMJ*, *322*, 763. doi:10.1136/bmj.322.7289.763

Lee, N., Chatzisarantis, N., & Hagger, M. S. (2016). Adequacy of the sequential-task paradigm in evoking ego depletion and how to improve detection of ego-depleting phenomena. *Frontiers in Psychology*, *7*, 136. doi:10.3389/fpsyg.2016.00136

Legault, L., & Inzlicht, M. (2013). Self-determination, self-regulation, and the brain: Autonomy improves performance by enhancing neuro-affective responsiveness to self-regulation failure. *Journal of Personality and Social Psychology, 105,* 123–138. doi:10.1037/a0030426

Lerdal, A., Wahl, A. K., Rustoen, T., Hanestad, B. R., & Moum, T. (2005). Fatigue in the general population: a translation and test of the psychometric properties of the Norwegian version of the fatigue severity scale. *Scandinavian Journal of Public Health*, *33*, 123-130. doi:10.1080/14034940410028406

Loge, J. H., Ekeberg, Ø., & Kaasa, S. (1998). Fatigue in the general Norwegian population: normative data and associations. *Journal of Psychosomatic Research, 45*, 53-65. doi:10.1186/s12955-017-0625-9

Lorist, M. M., Boksem, M. A., & Ridderinkhof, K. R. (2005). Impaired cognitive control and reduced cingulate activity during mental fatigue. *Cognitive Brain Research, 24*, 199-205. doi:10.1016/j.cogbrainres.2005.01.018

Luethi, M.S., Friese, M., Binder, J., Boesiger, P., Luechinger, R., & Rasch, B. (2016).Motivational incentives lead to a strong increase in lateral prefrontal activity after self-control exertion. *Social Cognitive and Affective Neuroscience, 11*, 1618–1626. doi:10.1093/scan/nsw073

Mackworth, J. F. (1964). Performance decrement in vigilance, threshold, and high-speed perceptual motor tasks. *Canadian Journal of Psychology, 18,* 209-223. doi:10.1037/h0083302

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive fatigue effects on physical performance during running. *Journal of Sport and Exercise Psychology, 36,* 375-381. doi:10.1123/jsep.2013-0249

Macridis, S., Johnston, N., Johnson, S., & Vallance, J. K. (2018). Consumer physical activity tracking device ownership and use among a population-based sample of adults. *PloS one, 13,* e0189298. doi:10.1371/journal.pone.0189298

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology, 106,* 857-864. doi:10.1152/japplphysiol.91324.2008

Martin, S. B., Morrow Jr, J. R., Jackson, A. W., & Dunn, A. L. (2000). Variables related to meeting the CDC/ACSM physical activity guidelines. *Medicine & Science in Sports & Exercise*, *32*, 2087-2092. doi:10.1097/00005768-200012000-00019

Martin Ginis, K. A., & Bray, S. R. (2010). Application of the limited strength model of self-regulation to understanding exercise effort, planning and adherence. *Psychology and Health*, *25*, 1147-1160. doi:10.1080/08870440903111696

McMorris, T., Barwood, M., Hale, B. J., Dicks, M., & Corbett, J. (2018). Cognitive fatigue effects on physical performance: A systematic review and meta-analysis. *Physiology & Behavior. 188*, 103-107. doi:10.1016/j.physbeh.2018.01.029

Mischel, W., Cantor, N., & Feldman, S. (1996). Principles of self-regulation: The nature of willpower and self-control. In E. T. Higgins & A. W.

Kruglanski (Eds.), *Social psychology: Handbook of basic principles* (pp. 329-360). New York, NY: Guilford Press.

Mitchell, M. S., Goodman, J. M., Alter, D. A., John, L. K., Oh, P. I., Pakosh, M. T., & Faulkner, G. E. (2013). Financial incentives for exercise adherence in adults: systematic review and meta-analysis. *American Journal of Preventive Medicine*, *45*, 658-667. doi:10.1016/j.amepre.2013.06.017

Moller, A.C., Deci, E.L., & Ryan, R.M. (2006). Choice and ego depletion: The moderating role of autonomy. Personality and Social Psychology Bulletin, 32, 1024–1036. doi:10.1177/0146167206288008

Müller, T. & Apps, M. A. (In Press). Motivational fatigue: A neurocognitive framework for the impact of effortful exertion on subsequent motivation. *Neuropsychologia*. Advance online publication. doi:10.1016/j.neuropsychologia.2018.04.030

Muraven, M., & Slessareva, E. (2003). Mechanisms of self-control failure: Motivation and limited resources. Personality and Social Psychology Bulletin, 29, 894–906. doi:10.1177/0146167203029007008

Noakes, T. D., St. Clair Gibson, A. & Lambert, E. V. (2005). From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *British Journal of Sports Medicine*, *39*, 120-124. doi:10.1136/bjsm.2003.010330

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *European Journal of Applied Physiology*, *114*, 1095-1105. doi:10.1007/s00421-014-2838-5

Pageaux, B., Marcora, S., & Lepers, R. (2013). Prolonged mental exertion does not alter neuromuscular function of the knee extensors. *Medicine & Science in Sports & Exercise*, *45*, 2254–2264. doi:10.1249/MSS.0b013e31829b504a,

Pageaux, B., Marcora, S. M., Rozand, V., & Lepers, R. (2015). Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. *Frontiers in Human Neuroscience*, *9*, 67. doi:10.3389/fnhum.2015.00067

Paluska, S. A., & Schwenk, T. L. (2000). Physical activity and mental health. *Sports Medicine*, *29*, 167-180. doi:10.2165/00007256-200029030-00003

Penedo, F. J., & Dahn, J. R. (2005). Exercise and well-being: a review of mental and physical health benefits associated with physical activity. *Current Opinion in Psychiatry*, *18*, 189-193. doi:10.1097/00001504-200503000-00013

Public Health Agency of Canada (2016). *Health status of Canadians 2016*. Government of Canada.

Ricci, J. A., Chee, E., Lorandeau, A. L., & Berger, J. (2007). Fatigue in the US workforce: prevalence and implications for lost productive work time.

Journal of Occupational and Environmental Medicine, 49, 1-10. doi:10.1097/01.jom.0000249782.60321.2a

Rozand, V., Lebon, F., Papaxanthis, C., & Lepers, R. (2015). Effect of mental fatigue on speed–accuracy trade-off. *Neuroscience, 297,* 219-230. doi:10.1016/j.neuroscience.2015.03.066

Rhodes, R. E., & Rebar, A. L. (2017). Conceptualizing and defining the intention construct for future physical activity research. *Exercise and Sport Sciences Reviews*, *45,* 209-216. doi:10.1249/jes.0000000000000127

Saunders, B., Lin, H., Milyavskaya, M., & Inzlicht, M. (2017). The emotive nature of conflict monitoring in the medial prefrontal cortex. *International Journal of Psychophysiology, 119,* 31-40. doi:10.31234/osf.io/5mts5

Shephard, R. J. (2001). Chronic fatigue syndrome. *Sports Medicine, 31*, 167-194. doi:10.2165/00007256-200131030-00003

Schücker, L., & MacMahon, C. (2016). Working on a cognitive task does not influence performance in a physical fitness test. *Psychology of Sport and Exercise*, *25*, 1-8. doi:10.1016/j.psychsport.2016.03.002

Smith, M. R., Coutts, A. J., Merlini, M., Deprez, D., Lenoir, M., & Marcora, S. M. (2016). Mental fatigue impairs soccer-specific physical and technical performance. *Medicine & Science in Sports & Exercise*, *48,* 267-276. doi:10.1249/mss.0000000000000762

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental fatigue impairs intermittent running performance. *Medicine & Science in Sports & Exercise*, *47*, 1682-1690. doi:10.1249/mss.0000000000000592

Tangney, J.P., Baumeister, R.F., & Boone, A.L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of Personality, 72*, 271–324. doi:10.1111/j.0022-3506.2004.00263.x

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The effects of mental fatigue on physical performance: a systematic review. *Sports Medicine, 47,* 1569-1588. doi:10.1007/s40279-016-0672-0

vanDellen, M. R., Hoyle, R. H., & Miller, R. (2012). The regulatory easy street: Self-regulation below the self-control threshold does not consume regulatory resources. *Personality and Individual Differences*, *52,* 898-902. doi:10.1016/j.paid.2012.01.028

Voce, A. C., & Moston, S. (2016). Does monitoring performance eliminate the ego depletion phenomenon and influence perception of time?. *Self and Identity, 15*, 32-46. doi:10.1080/15298868.2015.1074101

Wan, E. W., & Sternthal, B. (2008). Regulating the effects of depletion through monitoring. *Personality and Social Psychology Bulletin, 34,* 32-46. doi:10.1177/0146167207306756

Warburton, D. E., Nicol, C. W., & Bredin, S. S. (2006). Health benefits of physical activity: the evidence. *Canadian Medical Association Journal*, *174,* 801-809. doi:10.1016/b978-0-7506-5479-1.50004-2

Warm, J. S., Parasuraman, R., & Matthews, G. (2008). Vigilance requires hard mental work and is stressful. *Human Factors*, *50*, 433-441. doi:10.1518/001872008x312152

Wewers, M. E., & Lowe, N. K. (1990). A critical review of visual analogue scales in the measurement of clinical phenomena. *Research in Nursing & Health*, *13*, 227-236. doi:10.1002/nur.4770130405

Zering, J. C., Brown, D. M., Graham, J. D., & Bray, S. R. (2017). Cognitive control exertion leads to reductions in peak power output and V02 peak as well as increased perceived exertion on a graded exercise test to exhaustion. *Journal of Sports Sciences*, *35*, 1799-1807. doi:10.1080/02640414.2016.1237777

CHAPTER 2

Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance

Preamble

Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance is the first study in the dissertation series. The study examines whether a dose-response relationship exists for mental fatigue and physical performance. This study also examined several underlying psychological variables that may account for predicted reductions in physical performance. To do so, this study tested separate mediation models predicting cognitive control exertion → reduced task motivation/intrinsic motivation/affective valence/task self-efficacy and increased mental fatigue → reduced task performance.

The following manuscript is published in the journal *Sport, Exercise and Performance Psychology*. The published version of the manuscript (formatted according to the *Sport, Exercise and Performance Psychology* author guidelines) is included in the dissertation.

The copyright for this manuscript is currently held by the American Psychological Association (the publisher for *Sport, Exercise and Performance Psychology*). As stated on the Transfer of Copyright form "In return for copyright, APA hereby grants to the authors listed in Section 2 of this form, and the employers for whom the work was performed (if applicable), royalty-free, nonexclusive, limited licenses to… distribute or post all or portions of the above manuscript, after final acceptance for publication by APA, to the repository at the author(s) institution" (see Appendix E.1).

Contribution of Study 1 to overall dissertation

Study 1 provides the first evidence that downstream performance impairments are dependent on the experimental manipulation exceeding a critical mental fatigue threshold. Findings from Study 1 also suggest that negative changes in task self-efficacy indirectly (mediates) accounts for the negative change in physical endurance performance following effortful cognitive exertion. Thus, Study 1 contributes to the overall dissertation by showing that the potency of the experimental manipulation affects subsequent physical performance and that task self-efficacy is a motivational process that influences physical performance. Findings highlight the need to further test the role of motivation within the mental fatigue – physical performance relationship.

Sport, Exercise, and Performance Psychology
2017, Vol. 6, No. 4, 355–369

2157-3905/17/$12.00 http://dx.doi.org/10.1037/spy0000091

Graded Increases in Cognitive Control Exertion Reveal a Threshold Effect on Subsequent Physical Performance

Denver M. Y. Brown and Steven R. Bray
McMaster University

Exertion of cognitive control is associated with subsequent impairment of physical performance, however, current understanding is limited because manipulations have involved either high or low cognitive demands. The purpose of this study was to investigate the effects of graded exposure to cognitive control on subsequent physical performance, while also examining psychological processes that may mediate this relationship. Participants (N = 123) performed 2 isometric handgrip endurance trials separated by a cognitive control manipulation (Stroop task). Participants were randomized to 1 of 6 conditions: 0, 2, 4, 6, 8, or 10 min of exposure to the Stroop task. All manipulations were presented in a fixed, 12-min testing window. The cognitive task occupied the full window in the 10-min condition and the latter 2, 4, 6, or 8 min of the window in the other conditions, with a mild-attention task performed prior to the cognitive manipulation. The testing window consisted of 2-min blocks of the Stroop/filler task separated by 30-s rest periods in which affective valence and mental fatigue were assessed. Results showed handgrip endurance performance was uniformly unaffected following 0 to 4 min and uniformly impaired following 6 to 10 min of exerting cognitive control. Mental fatigue, affective valence and task self-efficacy were correlated with both cognitive control exertion and endurance performance, however task self-efficacy was the only mediating variable. Results are the first to show a negative carryover effect from cognitive to physical tasks occurs at a threshold between 4 and 6 min of cognitive task exposure.

Keywords: isometric exercise, mental fatigue, affective valence, self-efficacy, mediation

Cognitive control is a component of self-control referring to mental processes that allow people to override, inhibit or restrain behaviors (Inzlicht, Bartholow, & Hirsh, 2015). Accordingly, cognitive control is an instrumental aspect of performance in many domains such as academics and work (de Ridder, Lensvelt-Mulders, Finkenauer, Stok, & Baumeister, 2012) as well as sport and exercise. For example, in sport, cognitive control is essential to performance when athletes must cope with deceptive tactics of opponents attempting to "fake" them out, when they must focus attention in the face of distractions, and when they must persist at performance when nearing the limits of fatigue or exhaustion (Englert, 2016).

In the general psychology literature, there has been considerable research examining the effects of cognitive control tasks intended to induce mental fatigue and the negative downstream effects of mental fatigue on cognitive and behavioral performance (Boksem, Meijman, & Lorist, 2005; Van der Linden, & Eling, 2006). Recently, the effects of cognitive control exertion and mental fatigue have been extended to exercise and sport science. Several studies have demonstrated negative carryover effects of cognitive control exertion on time to exhaustion (Marcora, Staiano, & Manning, 2009) and time trial performance tasks (MacMahon, Schücker, Hagemann, & Strauss, 2014; Pageaux, Lepers, Dietz, & Marcora, 2014; Wagstaff, 2014) as well as muscular endurance tasks, including submaximal isometric handgrip contractions

---

Denver M. Y. Brown and Steven R. Bray, Department of Kinesiology, McMaster University.

Correspondence concerning this article should be addressed to Denver M. Y. Brown, Department of Kinesiology, McMaster University, 1280 Main Street West, IWC A201, Hamilton, Ontario, Canada L8S 4L8. E-mail: brownd32@mcmaster.ca

(Bray, Martin Ginis, Hicks, & Woodgate, 2008; Graham & Bray, 2015) and resistance exercises (Dorris, Power, & Kenefick, 2012; Graham, Martin Ginis, & Bray, 2016; Pageaux, Marcora, & Lepers, 2013). Accordingly, it is of theoretical and practical importance to understand the nature and extent of these effects in order to determine conditions that may enhance or compromise peak physical performance.

The strength model (Baumeister & Vohs, 2016) is one perspective that encompasses cognitive control as a major construct. This perspective proposes people's abilities to exert self-control are dependent upon a limited resource that is consumed or fatigued with use but can be replenished with rest (Baumeister, Vohs, & Tice, 2007). Studies generally show that after cognitive control is exerted for a period of time, performance of subsequent acts that require self-control in cognitive, emotional, and behavioral domains is negatively affected (Cunningham & Baumeister, 2016; Hagger, Wood, Stiff, & Chatzisarantis, 2010; Inzlicht, Gervais, & Berkman, 2015). Although it should also be noted that the magnitude and reliability of these effects has been the subject of recent controversy (Carter, Kofler, Forster, & McCullough, 2015; Carter & McCullough, 2013, 2014; Hagger et al., 2015).

Several studies have documented disruptions to physical performance following exertion of cognitive control. However, it is important to recognize that cognitive control manipulations have varied greatly in terms of cognitive control demands as well as duration. For example, several studies from the sport and exercise literature have used the AX version of the Continuous Performance Task, lasting 90 min (Marcora et al., 2009; Pageaux et al., 2013; Smith, Marcora, & Coutts, 2015), whereas others have used tasks (e.g., Stroop task) lasting 5 min or less (Bray et al., 2008; Graham & Bray, 2015). Despite a large number of studies having been undertaken, our understanding of the effects of cognitive control exertion on physical performance is limited because studies have exclusively involved simple between-groups or within-person comparisons using fixed manipulations contrasting a higher cognitive demand condition with either a control group or a lower cognitive demand condition. The assumption being the cognitive control manipulation is potent enough to elicit a significant response. To the best of our knowledge, no studies have attempted to evaluate whether a dose-response relationship exists.

Although no previous studies have investigated whether a dose-response relationship exists between cognitive control exertion and physical performance, there have been recent calls for such studies in the mainstream research area of self-control/ego-depletion (Lee, Chatzisarantis, & Hagger, 2016). Consistent with our argument above, Lee et al. (2016) noted that ascertaining the potency of self-control manipulations is critical. In their words, "If participants do not engage in effortful self-control on the first task, it is unlikely that they will be sufficiently depleted to show decrements in performance on subsequent tasks" (p. 2). In the only study to have investigated hierarchical doses of a self-control manipulation on subsequent self-control performance, van Dellen, Hoyle, and Miller (2012) exposed groups of participants to graded increments of a cognitive control task (i.e., 0-, 2-, 4-, or 6-min duration) and observed performance on a subsequent anagram-solving task that also required cognitive self-control. Results showed participants in the control condition (0 min) and the group exposed to two minutes of the initial cognitive control task did not demonstrate subsequent self-control impairments. In contrast, the groups exposed to four or six minutes of the initial task showed performance impairments on the anagram task, but did not differ significantly from one another. These findings suggested that rather than a graded dose-response relationship, there may be a threshold level at which cognitive control exertion leads to later performance impairments. From both a theoretical and practical standpoint, further research examining dose-response carryover effects is important to discern the extent to which sport and exercise performance may be compromised by cognitive control exertion.

In addition to a lack of attention devoted to dose-response issues, the literature investigating the aftereffects of cognitive control exertion on physical performance has largely focused on simple carryover effects, whereas few studies have investigated mechanistic processes that may explain why such effects occur. According to the process model of self-control (Inzlicht & Schmeichel, 2012; Inzlicht, Schmeichel, & Macrae, 2014), exerting self-control leads to temporary shifts in attention, motivation, and emotion, which serve to undermine voluntary exertion of self-control. Under the umbrella of emotional states, affective valence and mental fatigue are two constructs that have received some attention within self-control/ego-depletion and exercise performance literature. Evidence shows exposure to highly effortful cognitive control manipulations results in reduced positive affect as well as intensified feelings of mental fatigue (Dreisbach & Fischer, 2012; MacMahon et al., 2014; Marcora et al., 2009). Research in this area has also demonstrated less positive emotional states are associated with physical performance impairments (e.g., Marcora et al., 2009), yet no studies have examined emotional states as potential mediators of the relationship between cognitive control exertion and performance as predicted by the process model.

The process model also proposes motivational factors can account for the negative aftereffects of cognitive control exertion. Several studies have assessed motivation following cognitive control exertion. However, numerous operationalizations of motivation have been used (e.g., behavioral, self-report instruments) and have shown conflicting results. For instance, cognitive control exertion shows a negative effect on behavioral motivation evidenced by reduced willingness to continue effortful tasks (Boksem et al., 2005; Boksem & Tops, 2008; Inzlicht & Schmeichel, 2012). In contrast, self-report measures of motivation have failed to show effects in several studies (Marcora et al., 2009; Pageaux et al., 2013, 2014). Studies that have included self-report assessments of motivation have measured intrinsic motivation (Marcora et al., 2009; Pageaux et al., 2013, 2014) as well as task motivation (MacMahon et al., 2014; Schucker & MacMahon, 2016). None of these studies have shown significant effects of cognitive control exertion on motivation to perform physically demanding tasks.

Another motivational belief that influences self-control is task self-efficacy (Bandura, 1997). In two recent studies (Graham & Bray, 2015; Graham et al., 2016), researchers showed participants who exerted greater cognitive control performing an incongruent Stroop task reported lower task self-efficacy for physical endurance tasks than participants in a control condition. Further, in both studies task self-efficacy mediated the effect of cognitive control exertion on physical endurance performance, suggesting task self-efficacy may be an important motivational perception that is worthy of continued investigation.

Taken together, the literature thus far provides limited support for the predictions of the process model regarding motivational and emotional mechanisms that may account for the negative effects of cognitive control exertion on performance of physically demanding tasks. However, as far as we are aware there have been no attempts to assess multiple indicators of motivation and emotion as mediators of the cognitive control exposure–physical performance relationship in a single study.

In this study, we investigated the effects of linearly increasing loads of cognitive control exertion on submaximal endurance handgrip exercise. The underlying premise of the strength model is that some amount of a limited resource is consumed when self-control is exerted (Baumeister, Vohs, & Tice, 2007). Accordingly, we predicted that incremental increases in the duration of exposure to a task requiring cognitive control exertion would lead to incremental decreases in performance on a subsequent task requiring self-control in a linear dose-response manner, with progressively higher doses of cognitive control leading to progressively greater decreases in endurance.

The secondary purpose was to investigate psychological responses (i.e., mental fatigue, affective valence, intrinsic motivation, task motivation, task self-efficacy) to cognitive control exposure and examine these variables as potential mediators of the relationship between cognitive control exertion and physical endurance performance. We predicted that greater doses of cognitive control exposure would result in greater mental fatigue, reduced affective valence, reduced task and intrinsic motivation, and reduced task self-efficacy. Furthermore, it was hypothesized that mental fatigue, affective valence, task and intrinsic motivation, and task self-efficacy would mediate the relationship between cognitive control exposure and physical endurance performance.

Method

Participants and Design

Participants were untrained, recreationally active, undergraduate students ($N = 123$; 79 women, 44 men) with a mean age of 19.87 years

(*SD* = 1.58). We computed a sample size estimate using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009), based on the meta-analysis (Hagger et al., 2010) effect size of cognitive control manipulations on handgrip endurance (Cohen's $d = .64$). According to G*Power estimates, using $\beta = 0.80$ and $\alpha = .01$; for our primary analysis, a six condition, repeated measures between-groups design ($\alpha = .01$), with 42 participants was required, and for the mediation analysis (multiple linear regression with medium effect size and five predictors), a sample of 98 was sufficient. All participants were screened for contra-indicators of performing vigorous intensity exercise using the Physical Activity Readiness Questionnaire (PAR-Q; Thomas, Reading, & Shephard, 1992) and provided informed consent.

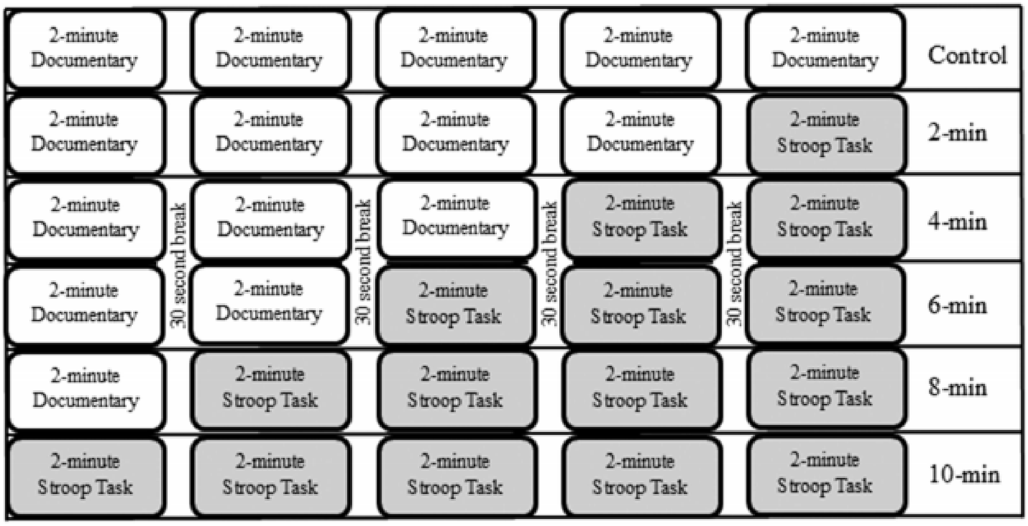
Using a single-blind, between-subjects design, participants were stratified by gender and randomized to one of the six experimental groups of varying cognitive control task exposure: 0- ($n = 21$), 2- ($n = 20$), 4- ($n = 20$), 6- ($n = 21$), 8- ($n = 21$), or 10-min ($n = 20$). Participants were instructed to avoid consuming caffeine and engaging in physical activity within 4 hr of testing, as well as to get at least 8 hr of devoted rest the night before their study session, and confirmed adherence to these requirements prior to testing. An institutional research ethics board reviewed and approved the study.

Measures

Demographics and moderate-to-vigorous physical activity. Demographics included self-reported gender and age. The International Physical Activity Questionnaire (Booth et al., 2003) was also used to assess moderate-to-vigorous physical activity (MVPA) during the 6 months prior to the study as a potential covariate as more active participants may also engage in activities that train muscular endurance.

Experimental Manipulations

The layout of the experimental manipulation is illustrated in Figure 1. The cognitive control task manipulations were delivered in a structured 12-min window consisting of five, 2-min blocks, each separated by 30-s breaks, in which participants provided ratings of mental fatigue and affective valence. As shown in the figure, the high cognitive control task occupied all five blocks in the 10-min exposure condition and the latter one, two, three, or four blocks of the window in 2-, 4-, 6-, and 8-min conditions, respectively. This arrangement ensured all participants completed their respective high cognitive control manipula-



2-minute Documentary		2-minute Documentary		2-minute Documentary		2-minute Documentary		2-minute Documentary	Control
2-minute Documentary		2-minute Documentary		2-minute Documentary		2-minute Documentary		2-minute Stroop Task	2-min
2-minute Documentary	30 second break	2-minute Documentary	30 second break	2-minute Documentary	30 second break	2-minute Stroop Task	30 second break	2-minute Stroop Task	4-min
2-minute Documentary		2-minute Documentary		2-minute Stroop Task		2-minute Stroop Task		2-minute Stroop Task	6-min
2-minute Documentary		2-minute Stroop Task		2-minute Stroop Task		2-minute Stroop Task		2-minute Stroop Task	8-min
2-minute Stroop Task		2-minute Stroop Task		2-minute Stroop Task		2-minute Stroop Task		2-minute Stroop Task	10-min

Figure 1. Conceptual layout of the experimental manipulations by condition.

tions during the last trial block of each manipulation window, allowing for identical recovery time between the cognitive control manipulation and the handgrip task. The low cognitive control task was performed as a "filler" task during blocks that did not involve high cognitive control task exposure. The low cognitive control task occupied all five blocks in the 0-min (control) condition.

High cognitive control 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 Stroop task has been used extensively in studies of self-control and found to yield medium-sized effects as a manipulation of cognitive control (d = .40) and large effects as a criterion task (d = .76; Hagger et al., 2010). 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-pt., Times New Roman font on a 17-in. flat screen computer monitor. Stimuli were visible on the monitor for 800 ms followed by a 100-ms intertrial 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 and ignore the printed word (e.g., for the word *BLACK* printed in "red" ink, they would say aloud the word *red*). Performing this task requires cognitive control in terms of response inhibition as participants are required to inhibit the dominant response of reading the word and replace it with the subordinate response of naming the font color (MacLeod, 1991).

Low cognitive control task. Participants watched 2-min segments of a documentary film (*Planet Earth*; Fothergill, Attenborough, & Fenton, 2007) on a 17-in. flat screen computer monitor. To ensure participants' attention was engaged while watching, they were asked to monitor the audio commentary and recorded instances when they heard a key word, *water*, which occurred at an average frequency of 1.2 per min. Similar documentary video manipulations have been used as low cognitive control tasks in other investigations as control tasks (e.g., Marcora et al., 2009).

Primary Outcome Measure

Isometric handgrip endurance task. The primary dependent variable was the amount of time participants maintained an isometric endurance handgrip contraction at 50% of their maximum voluntary contraction (MVC) using their dominant hand. The task was performed using a handgrip dynamometer (Model MLT003/D; ADInstruments) with graphic computer interface (PowerLab 4/25T; ADInstruments). To standardize task demands across participants, each participant performed two, 4-s all-out maximum handgrip squeezes on the dynamometer to determine their 100% MVC. Participants MVC values were recorded and evaluated as potential covariates. The average force recording obtained from a 1-s window at the peak of each MVC trial was analyzed to determine peak force generation and the greater force was halved to determine the 50% MVC target value for the endurance trials. For the isometric endurance trials, participants squeezed the handgrip dynamometer and were provided real-time feedback on a computer monitor showing a tracing of their force generation. A static line was displayed to identify the target force level (50% MVC). Participants were instructed to maintain the handgrip squeeze for as long as possible, keeping their force tracing line at, or slightly above, the target level and were given corrective feedback when the force dropped below the target level. The experimenter signaled the trial was complete when force fell below the 50% MVC line for longer than 2 s. Physical performance was defined as the number of seconds participants maintained the handgrip squeeze on the post-manipulation trial after controlling for their performance on Trial 1 (see Data Analysis section). During the endurance trials, the monitor was set up so participants had no knowledge of elapsed time or the magnitude of force generation (other than relative to the target force).

Psychological Measures and Mediators

Rating of perceived exertion. Ratings of perceived exertion (RPE) served as an indicator of physical effort exerted on the handgrip endurance tasks. RPE was recorded using Borg's CR-10 scale (Borg, 1998). Participants were instructed to rate their perception of exertion, that is, how heavy or strenuous the exercise felt to them based on the strain and fatigue in their muscles (Borg, 1998, p. 47) using a scale ranging from 0 (*no exertion at all*) to 10 (*maximal exertion*) following each isometric handgrip endurance trial.

Mental fatigue. A Visual Analogue Scale (VAS; Wewers & Lowe, 1990) was used to assess mental fatigue at five intervals during, and upon completion of, the cognitive control manipulation. To complete each measure, 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 *none at all* on the left hand side corresponding with 0 and *maximal* on the right hand side corresponding with 100. 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 cognitive manipulation, scores recorded at the 2-, 4:30-, 7-, 9:30-, and 12-min time points of the task were summed to calculate the area under the curve.

Affective valence. A modified version of Hardy and Rejeski's (1989) Feeling Scale (FS) was employed to measure affective valence at five intervals throughout, and upon completion of the cognitive control task. The FS is a single-item measure that is scored on an 11-point bipolar scale ranging from −5 to + 5 with anchors ranging from *very bad* (−5) to *very good* (+5). The FS was originally developed to assess affect during exercise, but was adapted for the cognitive task. Specifically, participants were instructed,

> While participating in challenging cognitive tasks, it is common to experience changes in mood. Some individuals find cognitive tasks pleasurable, whereas others find them to be unpleasant. Additionally, feelings may fluctuate across time. That is, one might feel good and bad a number of times while performing cognitive tasks.

Participants were asked to verbally report a number corresponding to their current feeling state at each interval. As was the case for mental fatigue, the cumulative effect of the experimental manipulation on affective valence was represented by the sum of scores recorded at the 2-, 4:30-, 7-, 9:30-, and 12-min time points of the cognitive control manipulation.

Intrinsic motivation. Five items from the effort and importance subscale of the Intrinsic Motivation Inventory (Ryan, 1982) were used to assess intrinsic motivation prior to performing each exercise task. Each item was prefaced with the stem, "For the handgrip squeezing task I am about to do. . . ." An example item from the scale is, "I am going to put a lot of effort into this." Each item was rated on a 7-point Likert scale ranging from 1 (*not true at all*) to 7 (*very true*). Internal consistency was acceptable for the scale at each administration (α ≥ .73).

Task motivation. To assess task motivation prior to each handgrip trial, a Visual Analogue Scale (VAS; Wewers & Lowe, 1990) was used. Participants were asked, "For the handgrip task you are about to complete, please mark the point on the line that represents your current state of motivation" and instructed to place an *X* at the point along a 100-mm line with the anchors ranging from *none at all* on the left hand side corresponding with 0 and *maximal* on the right hand side corresponding with 100. Scores were calculated by measuring the distance (in mm) that the *X* was placed from the left side of the scale.

Task self-efficacy. Task self-efficacy for the second endurance trial was assessed using an eight-item scale developed by Graham and Bray (2015). Each item was prefaced with the stem, "Compared with how long I went on the first trial, I am confident that I can hold on for. . . ." The individual items represented hierarchical gradations of performance that were relative to the participant's performance on the previous trial. The scale began at "25% as long (1/4 the amount)" and increased by 25% at each interval up to "200% as long (double the amount)." Participants rated their confidence for each item using an 11-point, 0 (*not at all confident*) to 10 (*totally confident*), scale as per guidelines provided by Bandura (2006). The task self-efficacy score was computed by averaging the ratings for each interval score. Internal consistency of the scale was considered acceptable (α = .82).

Procedure

Upon arrival at the laboratory, participants completed the PAR-Q, provided informed consent and completed the demographic questionnaires. Next, participants performed two 4-s, 100% MVC handgrip squeezes separated by one minute of rest. Following the second 100%

MVC, participants rested for five minutes, during which the experimenter set up the force feedback monitor and provided a 10-s demonstration of the isometric endurance handgrip task. Participants completed the intrinsic motivation scale and task motivation VAS and then performed the first isometric endurance handgrip trial. After completing the endurance trial, participants provided a rating of perceived exertion and rested for 3 min.

Participants were then stratified by gender and randomized to one of the six experimental groups and completed their respective cognitive control manipulations. At the conclusion of the manipulation, participants provided ratings of mental fatigue and affective valence followed by the measures of task self-efficacy, task motivation, and intrinsic motivation for the second handgrip endurance trial. Participants then completed the second handgrip endurance trial and provided a posttask rating of perceived exertion. Finally, participants were debriefed and given a $10 honorarium. Throughout the experimental procedure, there was no verbal/motivational encouragement at any time.

Data Analysis

Descriptive statistics were computed for all study variables. Separate one-way analyses of variance (ANOVAs) were computed for age, MVPA and MVC force to determine the effectiveness of the randomization protocol and potential covariates. Separate one-way ANOVAs were calculated for Trial 1 RPE and Trial 2 RPE. To evaluate the main hypothesis of the effects of cognitive control exposure on physical performance, a 6 (Condition; 0, 2, 4, 6, 8, 10) × 2 (Time; Trial 1 performance, Trial 2 performance) mixed ANOVA was computed. A series of 15 post hoc planned contrasts were conducted to compare the magnitude of trial–trial performance change between each pair of groups.

To evaluate the hypotheses relating to effects of the experimental manipulation on mental fatigue, affective valence, intrinsic motivation, task motivation, and task self-efficacy, separate one-way ANOVAs were computed with post hoc (Tukey) tests as follow-up to significant effects. Estimated effect sizes for the overall analyses are reported as partial eta squared (η_p^2).

To evaluate the relationships between manipulation condition, mental fatigue, affective valence, intrinsic motivation, task motivation, task self-efficacy, and performance change, we computed bivariate (Pearson's *r*) correlation coefficients. All psychological measures significantly correlated with condition and performance change were assessed as potential mediators using PROCESS software macro for SPSS to test for indirect (mediation) effects (Hayes, 2013). Bias-corrected bootstrap procedures utilizing 10,000 simulations were computed as recommended by Hayes and Scharkow (2013). A parallel multiple mediator model (Model 4) was computed to evaluate each potential mediator simultaneously. Effect size for mediation is reported as kappa-squared (κ^2). All statistical analyses were performed using IBM SPSS Version 20 (SPSS Version 20; IBM SPSS, 2011).

Results

Demographics and Potential Covariates

Separate one-way ANOVAs revealed no significant between-groups differences for age, $F(5, 117) = .43$, $p = .83$, MVPA, $F(5, 117) = .78$, $p = .56$, and MVC force, $F(5, 117) = .42$, $p = .84$, supporting the success of the randomization procedure. Descriptive statistics for these variables are shown in Table 1.

Dose-Response Analyses

Trial 1 and Trial 2 handgrip endurance performance scores are displayed by condition in Figure 2. Results of the repeated measures ANOVA demonstrated a significant effect for time, $F(1, 117) = 14.26$, $p < .001$, $\eta_p^2 = .11$. The main effect for condition was not significant, $F(5, 117) = .51$, $p = .77$, $\eta_p^2 = .02$, however, the Time × Condition interaction was significant, $F(5, 117) = 4.00$, $p = .002$, $\eta_p^2 = .15$. Post hoc planned contrasts revealed no differences between the 0-, 2-, and 4-min conditions (all *ps* $> .05$). There were also no differences between the 6-, 8-, and 10-min conditions (all *ps* $> .05$). However, each of the 0-, 2- and 4-min conditions were significantly different from each of the 6-, 8-, and 10-min conditions (all *ps* $< .05$), revealing a distinct response threshold between 4 min and 6 min of exposure to the high cognitive control task.

Table 1

Demographics, Moderate to Vigorous Physical Activity (MVPA) and Maximum Voluntary Contraction (MVC) Force by Condition

	Condition					
Measures	Control *M* (*SD*)	2-min *M* (*SD*)	4-min *M* (*SD*)	6-min *M* (*SD*)	8-min *M* (*SD*)	10-min *M* (*SD*)
Age	20.14 (1.62)	19.95 (1.50)	20.00 (2.03)	19.95 (1.63)	19.57 (1.16)	19.60 (1.54)
Gender: No. of males (%)	7 (33.33)	7 (35.00)	7 (35.00)	7 (33.33)	8 (38.10)	8 (40.00)
MVPA	341.90 (204.37)	404.75 (225.56)	360.75 (215.18)	308.81 (232.87)	323.81 (120.28)	405.75 (233.06)
MVC force	347.79 (113.72)	331.88 (73.95)	323.59 (71.34)	345.44 (99.69)	319.02 (101.75)	353.30 (117.17)

Note. MVPA = moderate-to-vigorous physical activity as minutes per week; MVC force = maximum voluntary contraction as Newton's. Control (n = 21), 2-min (n = 20), 4-min (n = 20), 6-min (n = 21), 8-min (n = 21), 10-min (n = 20).

Psychological Variable Analyses

Descriptive statistics and results of the post hoc, between-groups, comparisons for rating of perceived exertion, mental fatigue, affective valence, intrinsic motivation, task motivation, and task self-efficacy are presented in Table 2.

Rating of perceived exertion. Separate one-way ANOVAs showed no significant between-groups differences in RPE for Trial 1, $F(5, 117) = 1.28$, $p = .28$, or Trial 2, $F(5, 117) = 1.04$, $p = .40$, indicating all groups perceived exerting equivalent effort while performing the handgrip task.

Mental fatigue. The one-way ANOVA showed a significant effect, $F(5, 117) = 18.80$, $p < .001$, $\eta^2 = .45$. Post hoc tests revealed significant differences between the control (0-min) condition compared to the 4-, 6-, 8-, and 10-min conditions and the 2-min condition compared with the 6-, 8-, and 10-min conditions. The 10-min condition differed from each of the 4-, 6-, and 8-min conditions (all $ps < .05$). In brief, conditions that were ≥4 min apart in duration were significantly different from one another, with the exception of the 4- and 8-min conditions, which showed a nonsignificant trend ($p = .07$).

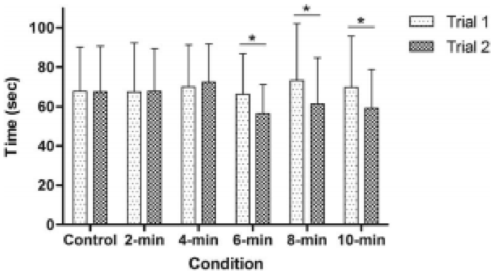


Figure 2. Trial 1 and Trial 2 handgrip endurance performance by Condition. * Indicates significant ($p < .05$) differences in Trial 1 - Trial 2 scores between Control, 2-min, 4-min.

Affective valence. The one-way ANOVA revealed a significant between-groups effect, $F(5, 117) = 4.28$, $p = .001$, $\eta^2 = .31$. Post hoc tests showed the control (0-min) group reported significantly greater positive affective valence compared with the 6-, 8-, and 10-min groups (all $ps < .05$), while no other between-groups effects were significant.

Intrinsic motivation. The one-way ANOVA for intrinsic motivation prior to Trial 1 revealed no between group differences, $F(5, 117) = 1.45$, $p = .21$, $\eta^2 = .06$. The ANOVA for intrinsic motivation prior to Trial 2 also showed a nonsignificant effect, $F(5, 117) = 1.28$, $p = .28$, $\eta^2 = .05$.

Task motivation. Task motivation prior to Trial 1 showed no between-groups differences, $F(5, 117) = 1.81$, $p = .12$, $\eta^2 = .07$. Task motivation was also not different between groups prior to Trial 2, $F(5, 117) = .09$, $p = .99$, $\eta^2 = .00$.

Task self-efficacy. The between-groups effect for task self-efficacy was not significant, $F(5, 117) = 1.57$, $p = .18$, $\eta^2 = .06$, however, guided by van Dellen et al.'s (2012) previous analysis, we pooled the data into lower (0 to 4 min) and higher task self-efficacy (6 to 10 min) clusters and evaluated the simple between-groups effect. The results were significant, $F(1, 121) = 7.23$, $p = .008$, $\eta^2 = .06$.

Indirect (Mediation) Effects

Correlation coefficients (Pearson r) between experimental condition, Trial 1–Trial 2 perfor-

Table 2
Psychological Measures by Condition

Psychological measures	Condition Control *M* (*SD*)	2-min *M* (*SD*)	4-min *M* (*SD*)	6-min *M* (*SD*)	8-min *M* (*SD*)	10-min *M* (*SD*)
Trial 1 RPE	6.33 (2.13)$_{a}$	6.13 (2.57)$_{a}$	7.58 (2.46)$_{a}$	6.62 (1.96)$_{a}$	6.02 (2.49)$_{a}$	6.09 (2.34)$_{a}$
Trial 2 RPE	7.33 (2.33)$_{a}$	6.95 (2.14)$_{a}$	7.90 (2.05)$_{a}$	6.67 (2.13)$_{a}$	6.55 (2.42)$_{a}$	6.83 (2.23)$_{a}$
Mental fatigue	10.34 (8.28)$_{ab}$	13.45 (8.31)$_{abc}$	19.82 (8.46)$_{bcde}$	24.58 (8.51)$_{cde}$	27.50 (8.81)$_{cdef}$	32.72 (10.43)$_{ef}$
Affective valence	16.48 (8.00)$_{a}$	13.81 (7.92)$_{ab}$	10.70 (8.05)$_{ab}$	8.57 (8.47)$_{b}$	6.72 (8.76)$_{b}$	6.90 (10.55)$_{b}$
Trial 1 intrinsic motivation	6.47 (.52)$_{a}$	6.48 (.57)$_{a}$	6.46 (.55)$_{a}$	6.15 (.44)$_{a}$	6.53 (.57)$_{a}$	6.45 (.45)$_{a}$
Trial 2 intrinsic motivation	6.21 (.99)$_{a}$	6.33 (.64)$_{a}$	6.29 (.69)$_{a}$	5.96 (.53)$_{a}$	6.41 (.86)$_{a}$	6.46 (.42)$_{a}$
Trial 1 task motivation	7.08 (2.27)$_{a}$	8.44 (1.40)$_{a}$	7.63 (1.89)$_{a}$	7.09 (1.57)$_{a}$	7.93 (1.72)$_{a}$	7.70 (1.44)$_{a}$
Trial 2 task motivation	6.96 (2.45)$_{a}$	7.08 (2.06)$_{a}$	6.76 (2.25)$_{a}$	6.90 (1.75)$_{a}$	6.72 (2.47)$_{a}$	7.04 (2.15)$_{a}$
Task self-efficacy	4.54 (1.00)$_{a}$	4.56 (1.68)$_{a}$	4.62 (1.10)$_{a}$	3.91 (.85)$_{a}$	4.19 (1.20)$_{a}$	3.92 (1.10)$_{a}$

Note. Values in the same row that do not share same subscript are significantly different at $p < .05$. Control ($n = 21$), 2-min ($n = 20$), 4-min ($n = 20$), 6-min ($n = 21$), 8-min ($n = 21$), 10-min ($n = 20$). RPE = rating of perceived exertion.

mance change, and each of the psychological variables are presented in Table 3. Results showed significant ($p < .05$) correlations for condition with affective valence ($r = -.38$), mental fatigue ($r = .67$), and task self-efficacy ($r = -.20$). Significant correlations ($p < .05$) were also found for performance change with affective valence ($r = .27$), mental fatigue ($r = -.24$), and task self-efficacy ($r = .40$). Neither task nor intrinsic motivation were correlated with condition or performance change (*p*s > .05) and were not included in the mediation models.

For the mediation analysis, a multiple mediator model was computed using the PROCESS macro for SPSS (Hayes, 2013) with indirect effects specified for mental fatigue, affective valence, and task self-efficacy. Experimental condition (dose) was the independent variable and performance change was the dependent variable. The magnitude of the coefficient for experimental condition as a direct effect on physical performance changed from −1.43 (*SE* = 0.39) in the simple prediction model to −1.07 (*SE* = 0.49) in the mediation model. A significant indirect effect was found for task self-efficacy (95% CI [−0.68, −0.05], $\kappa^2 = -0.30$). The indirect effects for mental fatigue and affective valence were not significant (see Figure 3).

Discussion

The purpose of the current study was to investigate the effects of linearly increasing doses

Table 3
Correlation Coefficients (Pearson's r) for Condition, Performance Change, and Psychological Measures

Measure	1	2	3	4	5	6	7
1. Condition	—						
2. Trial 1–Trial 2 performance change	–.32**	—					
3. Mental fatigue	.67**	–.24**	—				
4. Affective valence	–.38**	.27**	–.58**	—			
5. Intrinsic motivation	.08	–.03	–.10	.22*	—		
6. Task motivation	–.01	.10	–.09	.34**	.45**	—	
7. Task self-efficacy	–.20*	.40**	–.18	.19*	–.05	.10	—

Note. Intrinsic motivation and task motivation are represented by Trial 2 pre-task scores.
* $p \leq .05$. ** $p < .01$.

of cognitive control exertion on submaximal endurance handgrip exercise performance and to examine how intermediary psychological responses to cognitive control exposure may account for this relationship. Contrary to predictions, results did not show an incremental dose-response relationship between cognitive control exertion and physical performance. Rather, a nonlinear, threshold effect was evident as performance was uniformly unaffected following 0 to 4 min and uniformly impaired following 6 to 10 min of cognitive control. In partial support of our secondary hypotheses, increased levels of cognitive control exertion were associated with increased mental fatigue, decreased affective valence, and decreased task self-efficacy. However, intrinsic motivation and task motivation showed no significant associations with cognitive control exertion. Furthermore, although several psychological factors were correlated with task performance, only task self-efficacy was found to mediate the relationship between cognitive control exertion and handgrip endurance performance. Findings address several gaps in the literature through a systematic examination of varying doses of a cognitive control manipulation on physical endurance, while also assessing mechanistic psychological processes associated with cognitive control, which have received scant attention in previous research.

This study is the first to investigate the carryover effects of systematic increases of cognitive control exertion on physical performance. Contrary to our primary hypothesis, results failed to show negative carryover effects with smaller doses of cognitive control exposure (i.e., 2- and 4-min conditions), whereas the 6-, 8-, and 10-min conditions showed uniform negative effects on physical performance. Although this was not the predicted linear relationship between cognitive task exposure and performance, the results align with those of van Dellen and colleagues (2012), which also demonstrated a threshold carryover effect following exposure to cognitive control tasks. van Dellen et al.'s study utilized two sequential cognitive tasks and observed carryover effects for their manipulations lasting longer than 2 min.

Although differences in the timing of the threshold effect in the present study compared to van Dellen et al. (2012) may be attributable to differences in the manipulation tasks used and the nature of the criterion tasks (i.e., cognitive vs. behavioral), the results strongly support the idea that cognitive control manipulations must exceed a certain duration or level of exertion in order to induce significant aftereffects. However, results also suggest that within-domain effects (i.e., cognitive–cognitive) may be more sensitive to carryover effects than cross-domain effects (i.e., cognitive–behavioral). In short, our results indicate that self-control or ego-depletion effects are dependent on a manipulation dosage exceeding a critical threshold to be observed. Furthermore, when considered in concert with the findings of van Dellen et al., results suggest the amount of cognitive control required by the criterion task may also determine how strong the effect of the

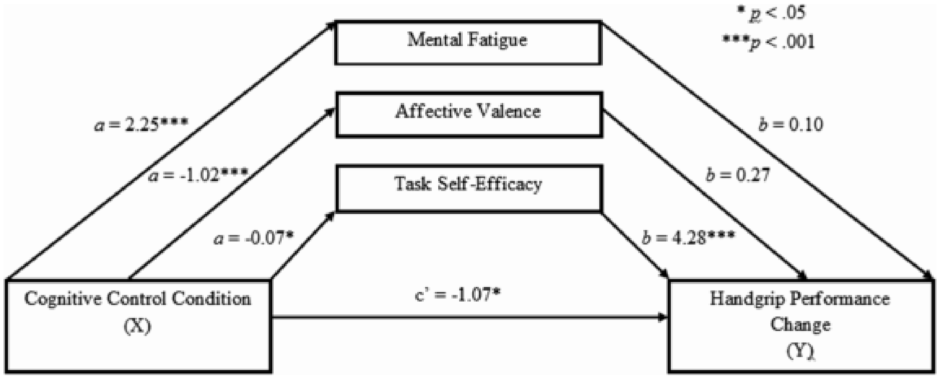


Figure 3. Multiple mediator model of the cognitive control exertion - isometric handgrip endurance performance relationship.

"depleting" manipulation task will be, as more demanding, or within-domain tasks may be more sensitive to prior cognitive control exertion than other tasks.

The emergence of a threshold effect is interesting for descriptive purposes, but also prompts consideration of mechanisms that cause performance decrements in tasks requiring physical self-control following cognitive control exertion. As we discuss subsequently, motivational and affective mechanisms are proposed to account for such effects, however, physiological explanations should also be important considerations. Recently, Evans, Boggero, and Segerstrom (2015) proposed self-control may be regulated by a hypothetical mechanism called the *Central Governor* that integrates sensory and perceptual signals to withdraw or avoid behavior when the organism's normal homeostatic limits are approached. Although application of the central governor perspective to self-control has been criticized (Inzlicht & Marcora, 2016), such a mechanism could explain why participants in the present study could exert up to four minutes of intense cognitive control with no aftereffects on physical endurance, but their endurance was uniformly scaled back following ≥6 min of prior cognitive exertion.

In addition to investigating the dose-response relationship, the present study was guided by the predictions of the process model of self-control (Inzlicht & Schmeichel, 2012; Inzlicht et al., 2014) to examine mechanistic factors (i.e., emotion, motivation) that may account for the effect of cognitive control exertion on later behavioral control of endurance exercise. Analyses of the intermediary factors revealed limited support for the process model. That is, despite observing a strong effect of cognitive control on endurance performance, intrinsic and task motivation were not associated with either the cognitive control manipulation or handgrip performance. Task self-efficacy was the only motivational variable correlated with experimental condition and performance change; however, task self-efficacy is not explicitly represented as a motivational factor in the process model.

Our analysis of emotion-based factors provided support for the process model's predictions insofar as results showed small to medium effect sizes for the associations between both mental fatigue and affective valence and experimental condition and performance (see Table 3), yet no indirect effects were detected in the mediation analysis. Thus, exerting cognitive control clearly lead to mental fatigue and reduced positive valence as predicted by the process model. However, the alterations in emotional states caused by cognitive control exertion do not appear to directly map onto changes in behavioral control. One interpretation of these findings is that changes in emotional states may need to exceed a certain magnitude in order to bring about significant changes in exercise endurance. In other words, people may be able to tolerate some emotional discomfort without it affecting behavior, but, past a certain point, negative shifts in emotional states can be disruptive to performance. This interpretation also aligns with Evans et al.'s (2015) proposition of a central governor or other central mechanisms imposing limits on self-control exertion.

Although we expected several psychological variables to mediate the cognitive control-endurance performance relationship, task self-efficacy was the only variable to produce a significant indirect effect in the analyses. These results extend recent findings by Graham and Bray (2015), who found task self-efficacy mediated the cognitive control-performance relationship using a dichotomous higher/lower cognitive control design. It is noteworthy that although task self-efficacy was significantly correlated with the experimental condition variable in the present study, the ANOVA showed no significant differences between the six groups. However, directed by a pooled-group analysis used by van Dellen et al. (2012), closer examination of the self-efficacy scores (see Table 2) show a significant uniform effect for the clusters of the lower (0 to 4 min) and higher (6 to 10 min) cognitive control conditions with ~0.5 units separating the two clusters. These results corroborate findings of Graham and Bray who used a Stroop-task manipulation lasting 5 min, which coincides with the threshold window (between 4- to 6-min Stroop exposure) for which we observed the negative carryover effect on handgrip endurance performance. These findings also support Bandura's (1997) theorizing regarding the role of task self-efficacy as a mediator and highlight the potency of self-efficacy as a determinant of physical performance (cf. Moritz, Feltz, Fahrbach, & Mack, 2000).

Another noteworthy finding is the similarly high ratings of perceived exertion reported by participants in all groups, regardless of the significant differences in endurance performance between the higher and lower cognitive control exertion conditions. These results support findings of Marcora et al. (2009) and Pageaux et al. (2013), who had participants perform endurance exercise tasks following a cognitive control manipulation and a control task using within-subjects designs. Their results showed participants reported similar levels of perceived exertion upon completing the physical endurance tasks, despite performing significantly worse following the cognitive control manipulation. However, those researchers also monitored perceived exertion during the physical endurance tasks and found ratings of exertion were also significantly higher following the cognitive control manipulations. These results suggest prior cognitive control exertion may intensify perceptions of physical exertion or sense of effort while performing physically demanding tasks (Kurzban, 2016).

Findings from the current study have implications for theory and research on self-control, but also with regards to sport and exercise performance. In terms of sport/exercise performance, results demonstrate cognitive control exertion results in negative carryover effects for physical performance, but that the effects are dependent upon exceeding a certain threshold of exertion. This threshold effect may be of importance for athletes and other performers (e.g., dance) across a range of scenarios where their performance requires sustained submaximal exertion or endurance to the point of extreme muscular fatigue. By recognizing or assessing when situations require high cognitive demands prior to or during competition, coaches may adjust their strategies to help athletes avoid suboptimal physical performance.

Another important implication of the findings relates to the recent debate over the legitimacy of the ego-depletion phenomenon. Some meta-analyses have shown exerting self-control for prolonged periods results in negative carryover effects on subsequent tasks requiring self-control that have a medium effect size (Hagger et al., 2010; Inzlicht et al., 2015). However, other meta-analyses (Carter et al., 2015; Carter & McCullough, 2013, 2014) have questioned the existence of the ego-depletion phenomenon, based on a number of studies that have found very small or null effects. Cunningham and Baumeister (2016) have suggested several methodological factors that call into question the validity of Carter et al.'s (2015) findings. However, results from the current study highlight the possibility that ego-depletion effects may be dependent on the magnitude of the manipulation dose and raise questions as to whether some manipulations employed in some studies may not have been powerful enough to demonstrate an effect. In particular, manipulation tasks lasting brief durations (i.e., less than 4 min) or lacking highly effortful cognitive control may lack the potency needed to produce an effect. Further analysis of the dose-response relationship between cognitive control and physical performance in the extant literature and continued examination in future research is greatly needed (cf. Lee et al., 2016).

Despite providing novel evidence relating to dose-response issues and mechanisms that may account for the cognitive control–performance relationship, the current study has a number of limitations. For one, using an isometric handgrip endurance exercise as the dependent variable lacks ecological validity due to the fact it is not a traditional sport or exercise task. Although endurance handgrip squeezing is not directly applicable to most sport performance situations, it allows for expression of maximum voluntary effort, which is a central feature of endurance and strength training (Ratamess et al., 2009; Seiler, 2010). Furthermore, reliance on a limited number of contributing muscles and relatively brief performance window allows for a highly controlled evaluation of behavioral responses to cognitive control exertion. Therefore, endurance handgrip squeezing allowed us to establish proof-in-principle of effects that should be further investigated using endurance performance tasks in more elaborate sport and exercise performance environments.

A further limitation relates to the cognitive control task. Several different variations of the Stroop task have been used in the ego/self-control depletion literature, including all-incongruent trials (e.g., DeWall et al., 2007), modified incongruent trials (e.g., Wallace & Baumeister, 2002), and a combination of congruent and incongruent trials (e.g., Govorun & Payne, 2006). Also, as noted earlier, the Stroop task has been used as both a criterion and manipulation variable in different studies (cf. Hagger et al., 2010) as well as for shorter (e.g., Bray et al., 2008) and longer (e.g., Webb & Sheeran, 2003) durations. The varied use of the Stroop task in the literature may raise concerns about its validity across the different manipulation durations involved in the current study. Future research using graded manipulations of other tasks requiring cognitive control is certainly needed before firm conclusions about a dose-response relationship can be drawn.

Another limitation of the Stroop task manipulation is the persistent and extreme cognitive demands it required. It is difficult to imagine tasks or situations requiring rapid sequences of response inhibition/cognitive control that last up to 10 min outside of a contrived laboratory situation. However, it is possible that people may experience unrelenting intrusive thoughts or emotions that require cognitive control for substantial periods of time (e.g., pre-performance anxiety). Our study has helped to illustrate that exerting cognitive control may not lead to negative aftereffects if it is limited to brief periods of exposure, which may have important implications for mental skills training programs. Furthermore, despite this limitation, the current study builds upon the only other study to have investigated a range of cognitive control manipulation doses (van Dellen et al., 2012) by assessing increasing grades of cognitive control exertion beyond 6-min duration as well as allowing examination of potential psychological mediators.

In conclusion, the current study revealed evidence of a threshold effect beyond 4-min exposure to an effortful cognitive control task which resulted in uniform decrements for subsequent physical performance on an isometric endurance handgrip squeezing task. Examination of potential mediating variables identified mental fatigue, affective valence and task self-efficacy as being significantly associated with cognitive control exertion and physical performance. However, task self-efficacy was the only variable found to mediate the cognitive control exertion–physical performance relationship. Overall, the results provide limited support for the process model of self-control. Further examination of emotional states and motivational variables as well as alternative mechanisms through which cognitive control exertion causes physical endurance impairments is clearly needed. Future research is also needed to extend examination of the effects observed in this study to field settings involving sport and exercise performance.

References

Bandura, A. (1997). *Self-efficacy: The exercise of control*. New York, NY: Freeman.

Bandura, A. (2006). Guide for constructing self-efficacy scales. In F. Pajares & T. C. Urdan (Eds.), *Self-efficacy beliefs of adolescents* (pp. 307–337). Greenwich, CT: Information Age Publishing.

Baumeister, R., & Vohs, K. (2016). Strength model of self-regulation as limited resource: Assessment, controversies, update. *Advances in Experimental Social Psychology, 54,* 67–127. http://dx.doi.org/10.1016/bs.aesp.2016.04.001

Baumeister, R. F., Vohs, K. D., & Tice, D. M. (2007). The strength model of self-control. *Current Directions in Psychological Science, 16,* 351–355. http://dx.doi.org/10.1111/j.1467-8721.2007.00534.x

Boksem, M. A., Meijman, T. F., & Lorist, M. M. (2005). Effects of mental fatigue on attention: An ERP study. *Cognitive Brain Research, 25,* 107–116. http://dx.doi.org/10.1016/j.cogbrainres.2005.04.011

Boksem, M. A., & Tops, M. (2008). Mental fatigue: Costs and benefits. *Brain Research Brain Research Reviews, 59,* 125–139. http://dx.doi.org/10.1016/j.brainresrev.2008.07.001

Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J. F., & Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity. *Medicine and Science in Sports and Exercise, 195,* 3508–1381.

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Bray, S. R., Martin Ginis, K. A., Hicks, A. L., & Woodgate, J. (2008). Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology, 45,* 337–343. http://dx.doi.org/10.1111/j.1469-8986.2007.00625.x

Carter, E. C., Kofler, L. M., Forster, D. E., & McCullough, M. E. (2015). A series of meta-analytic tests of the depletion effect: Self-control does not seem to rely on a limited resource. *Journal of Experimental Psychology: General, 144,* 796–815. http://dx.doi.org/10.1037/xge0000083

Carter, E. C., & McCullough, M. E. (2013). Is ego depletion too incredible? Evidence for the overestimation of the depletion effect. *Behavioral and Brain Sciences, 36,* 683–684. http://dx.doi.org/10.1017/S0140525X13000952

Carter, E. C., & McCullough, M. E. (2014). Publication bias and the limited strength model of self-control: Has the evidence for ego depletion been overestimated? *Frontiers in Psychology, 5,* 823. http://dx.doi.org/10.3389/fpsyg.2014.00823

Cunningham, M. R., & Baumeister, R. F. (2016). How to make nothing out of something: Analyses of the impact of study sampling and statistical interpretation in misleading meta-analytic conclusions. *Frontiers in Psychology, 7,* 1639. http://dx.doi.org/10.3389/fpsyg.2016.01639

de Ridder, D. T., Lensvelt-Mulders, G., Finkenauer, C., Stok, F. M., & Baumeister, R. F. (2012). Taking stock of self-control: A meta-analysis of how trait self-control relates to a wide range of behaviors. *Personality and Social Psychology Review, 16,* 76–99. http://dx.doi.org/10.1177/1088868311418749

DeWall, C. N., Baumeister, R. F., Stillman, T. F., & Gailliot, M. T. (2007). Violence restrained: Effects of self-regulation and its depletion on aggression. *Journal of Experimental Social Psychology, 43,* 62–76. http://dx.doi.org/10.1016/j.jesp.2005.12.005

Dorris, D. C., Power, D. A., & Kenefick, E. (2012). Investigating the effects of ego depletion on physical exercise routines of athletes. *Psychology of Sport and Exercise, 13,* 118–125. http://dx.doi.org/10.1016/j.psychsport.2011.10.004

Dreisbach, G., & Fischer, R. (2012). Conflicts as aversive signals. *Brain and Cognition, 78,* 94–98. http://dx.doi.org/10.1016/j.bandc.2011.12.003

Englert, C. (2016). The strength model of self-control in sport and exercise psychology. *Frontiers in Psychology, 7,* 314. http://dx.doi.org/10.3389/fpsyg.2016.00314

Evans, D. R., Boggero, I. A., & Segerstrom, S. C. (2015). The nature of self-regulatory fatigue and "ego depletion": Lessons from physical fatigue. *Personality and Social Psychology Review, 20,* 291–310. http://dx.doi.org/10.1177/1088868315597841

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41,* 1149–1160. http://dx.doi.org/10.3758/BRM.41.4.1149

Fothergill, A., Attenborough, D., & Fenton, G. (2007). *Planet earth: Fresh water.* Social Cognition: BBC Video.

Govorun, O., & Payne, B. K. (2006). Ego-depletion and prejudice: Separating automatic and controlled components. *Social Cognition, 24,* 111–136. http://dx.doi.org/10.1521/soco.2006.24.2.111

Graham, J. D., & Bray, S. R. (2015). Self-control strength depletion reduces self-efficacy and impairs exercise performance. *Journal of Sport & Exercise Psychology, 37,* 477–488. http://dx.doi.org/10.1123/jsep.2015-0064

Graham, J. D., Martin Ginis, K. A., & Bray, S. R. (2016). Exertion of self-control increases fatigue, reduces task self-efficacy, and impairs performance of resistance exercise. *Sport, Exercise, and Performance Psychology*. Advance online publication. http://dx.doi.org/10.1037/spy0000074

Hagger, M. S., Chatzisarantis, N. L., Alberts, H., Anggono, C. O., Batailler, C., Birt, A., . . . Zwienenberg, M. (2015). A multi-lab pre-registered replication of the ego-depletion effect. *Perspectives on Psychological Science, 2*. Advance online publication. http://dx.doi.org/10.1177/1745691616652873

Hagger, M. S., Wood, C., Stiff, C., & Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin, 136,* 495–525. http://dx.doi.org/10.1037/a0019486

Hardy, C. J., & Rejeski, W. J. (1989). Not what, but how one feels: The measurement of affect during exercise. *Journal of Sport & Exercise Psychology, 11,* 304–317. http://dx.doi.org/10.1123/jsep.11.3.304

Hayes, A. F. (2013). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach.* New York, NY: Guilford Press.

Hayes, A. F., & Scharkow, M. (2013). The relative trustworthiness of inferential tests of the indirect effect in statistical mediation analysis: Does method really matter? *Psychological Science, 24,* 1918–1927. http://dx.doi.org/10.1177/0956797613480187

IBM SPSS. (2011). IBM SPSS statistics base (Version 20). Armonk, NY: SPSS Inc.

Inzlicht, M., Bartholow, B. D., & Hirsh, J. B. (2015). Emotional foundations of cognitive control. *Trends in Cognitive Sciences, 19,* 126–132. http://dx.doi.org/10.1016/j.tics.2015.01.004

Inzlicht, M., Gervais, W. M., & Berkman, E. T. (2015). *Bias-correction techniques alone cannot determine whether ego depletion is different from zero: Commentary on Carter, Kofler, Forster, & McCullough, 2015*. Retrieved from http://ssrn.com/abstract=2659409. http://dx.doi.org/10.2139/ssrn.2659409

Inzlicht, M., & Marcora, S. M. (2016). The central governor model of exercise regulation teaches us precious little about the nature of mental fatigue and self-control failure. *Frontiers in Psychology, 7,* 656. http://dx.doi.org/10.3389/fpsyg.2016.00656

Inzlicht, M., & Schmeichel, B. J. (2012). What is ego depletion? Toward a mechanistic revision of the resource model of self-control. *Perspectives on Psychological Science, 7,* 450–463. http://dx.doi.org/10.1177/1745691612454134

Inzlicht, M., Schmeichel, B. J., & Macrae, C. N. (2014). Why self-control seems (but may not be) limited. *Trends in Cognitive Sciences, 18,* 127–133. http://dx.doi.org/10.1016/j.tics.2013.12.009

Kurzban, R. (2016). The sense of effort. *Current Opinion in Psychology, 7,* 67–70. http://dx.doi.org/10.1016/j.copsyc.2015.08.003

Lee, N., Chatzisarantis, N., & Hagger, M. S. (2016). Adequacy of the sequential-task paradigm in evoking ego-depletion and how to improve detection of ego-depleting phenomena. *Frontiers in Psychology, 7,* 136. http://dx.doi.org/10.3389/fpsyg.2016.00136

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Bulletin, 109,* 163–203. http://dx.doi.org/10.1037/0033-2909.109.2.163

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive fatigue effects on physical performance during running. *Journal of Sport & Exercise Psychology, 36,* 375–381. http://dx.doi.org/10.1123/jsep.2013-0249

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology, 106,* 857–864. http://dx.doi.org/10.1152/japplphysiol.91324.2008

Moritz, S. E., Feltz, D. L., Fahrbach, K. R., & Mack, D. E. (2000). The relation of self-efficacy measures to sport performance: A meta-analytic review. *Research Quarterly for Exercise and Sport, 71,* 280–294. http://dx.doi.org/10.1080/02701367.2000.10608908

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *European Journal of Applied Physiology, 114,* 1095–1105. http://dx.doi.org/10.1007/s00421-014-2838-5

Pageaux, B., Marcora, S. M., & Lepers, R. (2013). Prolonged mental exertion does not alter neuromuscular function of the knee extensors. *Medicine and Science in Sports and Exercise, 45,* 2254–2264. http://dx.doi.org/10.1249/MSS.0b013e31829b504a

Ratamess, N. A., Alvar, B. A., Evetoch, T. K., Housh, T. J., Kibler, W. B., & Kraemer, W. J., & the American College of Sports Medicine. (2009). American College of Sports Medicine position stand. Progression models in resistance training for healthy adults. *Medicine and Science in Sports and Exercise, 41,* 687–708. http://dx.doi.org/10.1249/MSS.0b013e3181915670

Ryan, R. M. (1982). Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of Personality and Social Psychology, 43,* 450–461. http://dx.doi.org/10.1037/0022-3514.43.3.450

Ryan, R. M., & Deci, E. L. (2000). Intrinsic and extrinsic motivations: Classic definitions and new directions. *Contemporary Educational Psychology, 25,* 54–67. http://dx.doi.org/10.1006/ceps.1999.1020

Schücker, L., & MacMahon, C. (2016). Working on a cognitive task does not influence performance in a physical fitness test. *Psychology of Sport and Exercise, 25,* 1–8. http://dx.doi.org/10.1016/j.psychsport.2016.03.002

Seiler, S. (2010). What is best practice for training intensity and duration distribution in endurance athletes? *International Journal of Sports Physiology and Performance, 5,* 276–291. http://dx.doi.org/10.1123/ijspp.5.3.276

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental fatigue impairs intermittent running performance. *Medicine and Science in Sports and Exercise, 47,* 1682–1690. http://dx.doi.org/10.1249/MSS.0000000000000592

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18,* 643–662. http://dx.doi.org/10.1037/h0054651

Thomas, S., Reading, J., & Shephard, R. J. (1992). Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Canadian Journal of Sport Sciences, 17,* 338–345.

van Dellen, M. R., Hoyle, R. H., & Miller, R. (2012). The regulatory easy street: Self-regulation below the self-control threshold does not consume regulatory resources. *Personality and Individual Differences, 52,* 898–902. http://dx.doi.org/10.1016/j.paid.2012.01.028

van der Linden, D., & Eling, P. (2006). Mental fatigue disturbs local processing more than global processing. *Psychological Research, 70,* 395–402. http://dx.doi.org/10.1007/s00426-005-0228-7

Wagstaff, C. R. (2014). Emotion regulation and sport performance. *Journal of Sport & Exercise Psychology, 36,* 401–412. http://dx.doi.org/10.1123/jsep.2013-0257

Wallace, H. M., & Baumeister, R. F. (2002). The effects of success versus failure feedback on further self-control. *Self and Identity, 1,* 35–41. http://dx.doi.org/10.1080/152988602317232786

Webb, T. L., & Sheeran, P. (2003). Can implementation intentions help to overcome ego-depletion? *Journal of Experimental Social Psychology, 39,* 279–286. http://dx.doi.org/10.1016/S0022-1031(02)00527-9

Wewers, M. E., & Lowe, N. K. (1990). A critical review of visual analogue scales in the measurement of clinical phenomena. *Research in Nursing & Health, 13,* 227–236. http://dx.doi.org/10.1002/nur.4770130405

Received September 14, 2016
Revision received February 23, 2017
Accepted February 26, 2017 ■

CHAPTER 3

Effects of mental fatigue on physical endurance performance and muscle activation are attenuated by monetary incentives

Preamble

Effects of mental fatigue on physical endurance performance and muscle activation are attenuated by monetary incentives is the second study in the dissertation series. This study investigated the hypothesis that offering a performance contingent monetary incentive would attenuate the negative carryover effects of mental fatigue on physical performance. This study also examined whether incentives restore muscle activation patterns (electromyography amplitude) typically witnessed following effortful cognitive exertion.

The following manuscript is published in the *Journal of Sport & Exercise Psychology*. The published version of the manuscript (formatted according to the *Journal of Sport & Exercise Psychology* author guidelines) is included in the dissertation as accepted for publication in the *Journal of Sport & Exercise Psychology*. The published version of this manuscript can be found at: https://doi.org/10.1123/jsep.2017-0187.

The copyright for this manuscript is currently held by Human Kinetics (the publisher for the *Journal of Sport & Exercise Psychology*). As stated on the Transfer of Copyright form, “The authors reserve the following rights: … The right to use all or part of this article in future works of their own, such as dissertations, lectures, reviews, or textbooks.” (see Appendix E.2).

Contribution of Study 2 to overall dissertation

Study 2 builds upon Study 1 by providing first evidence that incentives moderate the mental fatigue – physical performance relationship. Findings also showed that providing a motivational impetus can attenuate fatigue-induced muscle activation increases typically witnessed following effortful cognitive exertion, demonstrating evidence of patterns witnessed in a non-fatigued state.

Journal of Sport & Exercise Psychology, 2017, 39, 385-396
https://doi.org/10.1123/jsep.2017-0187

Human Kinetics
ORIGINAL RESEARCH

Effects of Mental Fatigue on Physical Endurance Performance and Muscle Activation Are Attenuated by Monetary Incentives

Denver M.Y. Brown and Steven R. Bray
McMaster University

Physical performance is impaired following cognitive control exertion. Incentives can ameliorate adverse carryover effects of cognitive control exertion but have not been investigated for physical endurance. This study examined the effect of monetary incentives on physical performance and muscle activation following exposure to a mentally fatiguing, cognitive control task. Participants ($N = 82$) performed two isometric endurance handgrip trials separated by a 12-min cognitive control manipulation using a 2 (high cognitive control [HCC]/low cognitive control [LCC]) × 2 (incentive/no incentive) design. Mental fatigue was significantly higher in the HCC conditions. Performance decreased in the HCC/no incentive condition but was unaffected in the HCC/incentive condition, which did not differ from the low cognitive control conditions. Electromyography data revealed increased muscle activation in the HCC/no incentive condition, which was also attenuated in the HCC/incentive condition. Findings show that incentives counteract the negative effects of HCC on physical endurance and alter central drive to motor units.

Keywords: exercise performance, isometric, motivation

Self-control refers to one's ability to alter prepotent behavioral, emotional, and cognitive responses based on a set of standards (Baumeister & Vohs, 2016). Self-control is required across a wide range of behaviors to attain beneficial outcomes, such as career success or improved health (de Ridder, Lensvelt-Mulders, Finkenauer, Stok, & Baumeister, 2012). Self-control capabilities vary across individuals (Baumeister, Heatherton, & Tice, 1994; Mischel, Cantor, & Feldman, 1996). In this regard, self-control can be conceptualized as a stable *trait* characteristic (Baumeister et al., 1994; Tangney, Baumeister, & Boone, 2004). However, self-control can also be *state* specific, whereby people's self-control can be stronger or weaker depending on one's circumstances at a given time (Baumeister, 2014; Baumeister et al., 1994; Baumeister, Vohs, & Tice, 2007).

A prominent theory of self-control is the strength model (Baumeister & Vohs, 2016). The strength model posits that self-control is dependent upon energetic resources, and as resources are depleted, or consumed, people's abilities to exert self-control diminish for a period of time until replenished with rest (see Muraven & Baumeister, 2000 for a comprehensive review of the assumptions of the strength model). Although the nature of the self-control resource has not been definitively established (e.g., glucose hypothesis; Beedie & Lane, 2012; Gailliot & Baumeister, 2007; Gailliot et al., 2007), a substantial body of research has demonstrated negative carryover effects of initial self-control exertion on the performance of subsequent self-control tasks (Hagger, Wood, Stiff, & Chatzisarantis, 2010). Although the magnitude and reliability of this effect have been subjects of controversy (Carter, Kofler, Forster, & McCullough, 2015; Hagger et al., 2016), studies have generally supported a negative carryover effect from one self-control task to another with medium to large effect sizes (Cunningham & Baumeister, 2016; Hagger et al., 2010; Inzlicht, Gervais, & Berkman, 2015).

Overcoming urges to succumb to short-term gratification involves engaging cognitive control, a central component of self-control, which allows us to consciously alter our responses to align with goals and norms (Inzlicht, Bartholow, & Hirsh, 2015). Cognitive control is important for many tasks of daily living as well as an instrumental aspect of performance for sport and exercise (Englert, 2016). Numerous studies have demonstrated negative carryover effects from tasks involving high levels of cognitive control exertion on performance of physically demanding tasks. In these studies, negative carryover effects are typically investigated using a sequential-task paradigm, where participants perform an initial task requiring cognitive control and shortly

---

Denver M.Y. Brown and Steven R. Bray are with the Department of Kinesiology, McMaster University, Hamilton, Ontario, Canada. Address author correspondence to Denver M.Y. Brown at brownd32@mcmaster.ca.

thereafter perform a task that requires physically demanding effort. For example, after completing a cognitive task designed to deplete self-control, negative performance effects have been observed for whole-body cardiovascular endurance tasks (Englert & Wolff, 2015; MacMahon, Schücker, Hagemann, & Strauss, 2014; Marcora, Staiano, & Manning, 2009; Pageaux, Lepers, Dietz, & Marcora, 2014; Zering, Brown, Graham, & Bray, 2017) and strength exercises (Bray, Martin Ginis, Hicks, & Woodgate, 2008; Brown & Bray, 2017; Dorris, Power, & Kenefick, 2012; Graham & Bray, 2015; Graham, Martin Ginis, & Bray, 2017).

Although negative carryover effects from tasks involving cognitive control to physical strength or endurance tasks are consistent, there has been little theoretical or empirical development in terms of identifying the mechanisms or mediating variables that may account for these effects in the exercise self-regulation literature or the self-regulation literature, in general (cf. Lurquin & Miyake, 2017). However, a recent series of investigations has shown that self-efficacy may play an important role in the translation of self-control strength depletion to physical performance tasks (Brown & Bray, 2017; Graham & Bray, 2015; Graham et al., 2017). Those authors proposed that exertion of self-control leads to sensations of fatigue that may reduce self-efficacy and otherwise interfere with physical performance.

Fatigue is characterized differently across a range of academic and clinical disciplines. However, from a psychological perspective, fatigue has been defined as the subjective perceptions associated with prolonged cognitively effortful tasks, which result in feelings of tiredness, lack of energy, or boredom (Hockey, 2013). This psychophysiological subjective state has been operationalized using a variety of self-report questionnaires (e.g., Profile of Mood States) or visual analog scale indicators. In support of fatigue as a potential mediating mechanism in the self-control depletion process, Hagger et al.'s (2010) meta-analysis revealed that exerting cognitive control during the initial task in a sequential-task paradigm had a medium-sized effect ($d = 0.44$) on subjective ratings of fatigue. A recent meta-analysis examining manipulations of cognitive control resulting in mental fatigue also revealed a medium to large effect ($d = 0.74$) of mental fatigue on subsequent self-control task performance (Clarkson, Otto, Hassey, & Hirt, 2016).

Baumeister and Vohs (2016) suggest that heightened perceptions of mental fatigue may be indicative of depleted resources (i.e., ego depletion) and may be a symptom of exerting self-control, which makes the prospect of performing future tasks that draw upon those resources appear more daunting or feel more effortful (see also Hagger et al., 2010). Interestingly, this account is supported by evidence from studies investigating the effect of mental fatigue induced by cognitive control tasks on perceived exertion and performance of physically demanding exercise tasks (Van Cutsem et al., 2017). Van Cutsem et al. (2017) concluded that mental fatigue causes alterations in physical performance and perceived exertion for tasks that involve prolonged endurance at submaximal levels. That is, when people self-regulate exercise at a constant level of perceived exertion, their physical performance is decreased when they are mentally fatigued (e.g., MacMahon et al., 2014) compared with when they are not fatigued. Conversely, when the physical performance demands of exercise are held constant, perceived exertion experienced while exercising is increased when participants are mentally fatigued (e.g., Marcora et al., 2009). However, it is not yet clear what causes these changes in ratings of perceived exertion (RPE) or performance.

Physiological alterations in response to mental fatigue may lead to increased ratings of perceived effort and declines in physical performance. Yet, few studies have assessed physiological changes that occur when people engage in self-control when they are fatigued (Segerstrom, Smith, & Eisenlohr-Moul, 2011). In the exercise domain, studies have measured muscle activation (i.e., motor unit activation) while performing isometric muscle contractions (Bray et al., 2008; Graham, Sonne, & Bray, 2014) and endurance cycling (Pageaux, Marcora, Rozand, & Lepers, 2015). These studies have shown that electromyography (EMG) amplitude in the contracting muscles increases among people who exercise after performing a mentally fatiguing cognitive task compared with those who exercise after a nonfatiguing control task. These increases in EMG amplitude can be indicative of several phenomena (Farina, Merletti, & Enoka, 2004; Heckman & Enoka, 2012), but generally infer there are different motor unit recruitment patterns being orchestrated through efferent pathways by the motor cortex when people are mentally fatigued compared with when they are not.

In addition to muscle activation, measurement of neural activation using functional magnetic resonance imaging while participants perform sequences of effortful cognitive control tasks has shown interesting results as well. For example, performing an initial task requiring cognitive control led to decreased activation in specific brain areas (i.e., inferior frontal gyrus of the prefrontal cortex) and also led to poorer performance on subsequent cognitive control tasks (Friese, Binder, Luechinger, Boesiger, & Rasch, 2013; Luethi et al., 2016; Persson, Larsson, & Reuter-Lorenz, 2013). Interestingly, Luethi et al. (2016) showed that when participants, whose brain activation was decreased after the initial self-control depletion task, were offered a motivational incentive prior to performing the subsequent cognitive control task, neural activation in those same brain regions increased, and performance increased to levels consistent with (or better than) participants who had not performed the initial cognitive control task. These results suggest that offering motivational incentives may increase performance by activating brain regions that are integral to task performance or part of a network that orchestrates self-control over thoughts, emotions, and actions.

Motivation is now considered a major factor in cognitive control and behavior (Baumeister & Vohs, 2016; Botvinick & Braver, 2015; Inzlicht & Schmeichel, 2012). According to the strength model of self-control, increasing motivation (e.g., provision of an incentive) is an important moderating mechanism insofar as demonstrating ego depletion is not an all or none phenomenon. That is, people manage or conserve their resources, and this is dependent on several factors including motivation. Therefore, whenever people are provided a motivational impetus to increase performance, people further draw upon their self-control resources even when in a depleted state (Graham, Bray, & Martin Ginis, 2014; Muraven, Shmueli, & Burkley, 2006).

In research using the sequential-task paradigm, studies that manipulate motivation through perceived choice/autonomy and performance contingent rewards show performance can be improved significantly and attenuate the ego-depletion effect for tasks requiring cognitive control (Legault & Inzlicht, 2013; Luethi et al., 2016; Moller, Deci, & Ryan, 2006; Muraven & Slessareva, 2003) and physical control (Graham, Bray, & Martin Ginis, 2014). However, there have been no studies that have manipulated motivation to investigate the effects on performance and muscle activation patterns during performance of a physical self-control task. Assessing muscle activation during exercise under conditions of enhanced motivation and fatigue or self-control depletion would provide novel and potentially important information about how the "motivated" brain may alter the descending commands from the motor cortex to the motor units in the muscles to modify task performance.

The primary purpose of this study was to investigate the effect of a monetary incentive on physical endurance performance following exposure to a mentally fatiguing cognitive control task. The secondary purpose was to investigate the effects of mental fatigue and incentives on muscle activation (i.e., EMG amplitude) during physical performance. Based on prior ego-depletion research in exercise (Brown & Bray, 2017; Englert & Wolff, 2015; Graham & Bray, 2015; Graham et al., 2017), we hypothesized that exposure to a mentally fatiguing high cognitive control (HCC) task would result in subsequent physical performance decrements when compared with a nonfatiguing low cognitive control (LCC) task. Based on prior research investigating the effect of incentives on ego depletion and performance (Luethi et al., 2016; Muraven & Slessareva, 2003), we hypothesized that providing a monetary incentive would attenuate performance such that HCC combined with an incentive would lead to similar performance to the LCC condition. Based on previous research on muscle activation (Bray et al., 2008; Graham, Sonne, & Bray, 2014; Pageaux et al., 2014), we predicted that exposure to a mentally fatiguing, HCC task would cause greater increases in EMG amplitude change during the muscular endurance task compared with a nonfatiguing LCC task. Following our prediction that incentives should attenuate the ego-depletion performance effect, we hypothesized that the incentive would also attenuate muscle activation such that HCC combined with an incentive would lead to similar EMG amplitude patterns as those seen in the LCC conditions during the exercise task.

Methods

Participants and Design

A total of 82 recreationally active university students (30 males and 52 females) with a mean age of 20.02 ($SD = 1.52$) years participated in the study. We computed a sample size estimate using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009) based on Hagger et al.'s (2010) meta-analysis effect size of cognitive control manipulations on handgrip endurance (Cohen's $d = 0.64$). According to G*Power estimates, using $\beta = 0.80$ and $\alpha = .01$, for our primary analysis: a four-condition analysis of covariance (ANCOVA) design using participants' first handgrip endurance duration as the covariate, 66 participants were required. To account for potential data loss due to problems with EMG measurements, 82 participants were recruited, but no data were lost. All participants were screened for contraindicators of performing vigorous-intensity exercise using the Physical Activity Readiness Questionnaire (Thomas, Reading, & Shephard, 1992) and provided informed consent prior to participation.

The study employed a single-blind, 2 (HCC/LCC) × 2 (incentive/no incentive) between-subjects design. Participants were stratified by sex and randomized to one of the experimental conditions. The incentive was $10 Canadian dollars (~$7.50 U.S. dollars). Participants were instructed to avoid consuming caffeine and engaging in physical activity within 4 hr of testing as well as to get at least 8 hr of devoted rest the night before their study session and confirmed adherence to these requirements prior to testing. The McMaster University Research Ethics Board reviewed and approved the study.

Measures

Demographics, moderate-to-vigorous physical activity, and trait self-control. Demographic information for self-reported sex, age, average weekly moderate-to-vigorous physical activity (MVPA) during the 6 months prior to the study, and trait self-control were obtained for descriptive purposes as well as to include as potential covariates in the event of nonequivalent group composition. The International Physical Activity Questionnaire (Booth et al., 2003) was used to assess MVPA. The brief version of the Self-Control Scale (Tangney et al., 2004) was employed to measure participants' general abilities to control thoughts, impulses, and emotions, and maintain self-discipline. Participants rated 13 items (e.g., *I am good at resisting temptation*) on a 5-point Likert-type scale ranging from 1 (*not at all like me*) to 5 (*very much like me*).

Primary Outcome Measures

Isometric handgrip endurance task. The primary dependent variable was the duration (in seconds) participants maintained an isometric endurance handgrip contraction at 50% of their maximum voluntary contraction (MVC) using their dominant hand. Isometric handgrip endurance tasks have been used in several studies examining the effects of cognitive control exertion on physical performance (e.g., Bray et al., 2008; Brown & Bray, 2017; Graham & Bray, 2015). The task was performed using a handgrip dynamometer (model MLT003/D; ADInstruments, Colorado Springs, CO) with graphic computer interface (PowerLab 4/25T; ADInstruments). To standardize task demands across participants, each participant performed two 4-s maximum handgrip squeezes on the dynamometer to determine their 100% MVC. The average force recording obtained from a 1-s window at the peak of each MVC trial was analyzed to determine peak force generation, and the greater force was halved to determine the 50% MVC target value for the endurance trials. Participant's MVC values were recorded and evaluated as potential covariates.

For the isometric endurance trials, participants squeezed the handgrip dynamometer and were provided instantaneous feedback on a computer monitor showing a tracing of their force generation. A static line was displayed to identify the target force level (50% MVC). Participants were instructed to maintain the handgrip squeeze for as long as possible, keeping their force tracing line at, or slightly above, the target level and were given corrective feedback when the force dropped below the target level. The experimenter signaled the trial was complete when force fell below the 50% MVC line for longer than 2 s. Physical performance was defined as the change in the number of seconds participants maintained the handgrip squeeze on the post-manipulation trial compared with their performance on Trial 1 (see Data Analysis section). During the endurance trials, participants had no knowledge of elapsed time or the magnitude of force generation (other than relative to the target force).

Proportional EMG amplitude. Surface EMG of the forearm flexors was recorded during each handgrip squeezing trial as a physiological measure of muscle activation. In preparation, skin was cleaned and lightly abraded on the forearm, and disposable surface electrodes were placed 2 cm apart on the muscle belly of the flexor carpi radialis. A ground electrode was placed on the bony prominence of the medial epicondyle of the humerus. The surface EMG signal was amplified, digitized, and continuously streamed using a PowerLab ML870 data acquisition system (ADInstruments) to a PC at 4000 Hz. To compute the proportional EMG amplitude scores, the EMG signal was band-pass filtered from 20 to 500 Hz, full-wave rectified, and normalized as a percentage of the greatest value (amplitude) recorded during a 1-s window from each participant's pretrial MVC. Proportional EMG amplitude scores (% of MVC) were computed at 0%, 25%, 50%, 75%, and 100% iso-time (see Data Analysis section) for Trial 1 and Trial 2, and the difference score at each iso-time was used to represent the change in proportional EMG amplitude. All EMG processing was performed using LabChart 8 data analysis software (ADInstruments).

Intermediary Measures

To assess the effects of the manipulations and control for potential confounding variables, we assessed (a) RPE to determine how much effort participants put into each handgrip trial, (b) task motivation to determine how motivated participants were to perform their best on each handgrip trial, and (c) mental fatigue to determine how fatigued participants in the HCC conditions were compared with participants in the LCC conditions.

Ratings of perceived physical exertion. RPE were recorded using Borg's (1998) 10-point CR-10 scale. Participants were instructed to rate their perception of exertion, that is, how heavy or strenuous the exercise felt to them based on the strain and fatigue in their muscles (Borg, 1998, p. 47) using the scale ranging from 0 (*no exertion at all*) to 10 (*maximal exertion*) following each isometric handgrip endurance trial.

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

Mental fatigue. Mental fatigue was assessed using a VAS that is commonly employed within the mental fatigue—physical performance literature (e.g., Ishii et al., 2015; Smith et al., 2016). The mental fatigue VAS has demonstrated strong psychometric properties (Wood, Magnello, & Jewell, 1990). We assessed mental fatigue during the 30-s break following each 2-min interval of the cognitive control manipulation. To complete each measure, participants were instructed: "For the task you just completed, 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 "none at all" on the left-hand side corresponding with 0 and "maximal" on the right-hand side corresponding with 100. Scores were calculated by measuring the distance (in millimeters) that the "X" was placed from the left side of the scale. To assess the cumulative effect of the cognitive manipulation, scores recorded at the 2-, 4-, 6-, 8-, and 10-min time points of the task were summed to calculate the area under the curve.

Experimental Manipulations

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

HCC (fatigue) task. Participants performed a 10-min computerized version of the incongruent Stroop task (Stroop, 1935) using Presentation™ software (version 17.0; Neurobehavioral Systems, Inc., Berkeley, CA; www.neurobs.com). The Stroop task has been used extensively in studies of self-control and found to yield medium-sized effects ($d = 0.40$) as a manipulation of cognitive control (Hagger et al., 2010). The task was set up such that participants performed five 2-min blocks each consisting of 135 trials that were separated by four 30-s breaks during which participants rated their level of mental fatigue. The word stimuli (i.e., BLACK, BLUE, GREEN, RED, PINK, and GRAY) were presented on a white background in 48-size Times New Roman font on a 17-in. flat-screen computer monitor. Stimuli were visible on the monitor for 800 ms followed by a 100-ms intertrial interval in which the screen was blank. Participants were instructed to respond as quickly and accurately as possible to each trial by saying aloud the color of the font in which the word was presented and ignore the printed word (e.g., for the word "black" presented in "red," they would say aloud the word "red"), which required participants to inhibit their dominant response of reading the printed word and instead replace it with the subordinate response of naming the ink color. Performing this cognitive control task requires response inhibition, a central component of executive function.

LCC task. Participants watched a 10-min segment of a documentary film (*Planet Earth*; Fothergill, Attenborough, & Fenton, 2007) on a 17-in. flat-screen computer monitor. Similar to the Stroop task, the film was shown as a sequence of five 2-min clips, separated by 30-s breaks during which participants rated their level of mental fatigue. To ensure attention was engaged throughout the duration of the task, participants were asked to monitor the audio commentary and recorded instances when they heard a keyword: *water*. Similar documentary video manipulations have been used as LCC tasks in other investigations as control tasks (e.g., Marcora et al., 2009; Zering et al., 2017). Zering et al. (2017) reported that this control task manipulation induces no changes in participants' affective states or arousal indicating participants find the task neither relaxing nor boring.

Procedure

Upon arrival at the laboratory, participants completed the Physical Activity Readiness Questionnaire, provided informed consent, and completed the demographic questionnaires as well as the trait self-control scale. They were then fitted with EMG recording electrodes and performed two 4-s 100% MVC handgrip squeezes separated by 1 min of rest. Following the second 100% MVC, participants rested for 5 min during which the experimenter set up the force feedback monitor and provided a 10-s demonstration of the endurance handgrip task. Participants completed the pretask motivation measure and then performed the first isometric endurance handgrip trial. After completing the endurance trial, participants provided RPE for the handgrip task and rested for 3 min.

Participants were then stratified by sex and randomized to one of the four experimental conditions. They then completed their respective cognitive control manipulation tasks and reported their feelings of mental fatigue after each 2-min block. At the conclusion of the manipulation, participants provided a final rating of mental fatigue and pretrial task motivation scale for the second handgrip endurance trial. Prior to beginning the second handgrip trial, participants in the incentive conditions were informed by the experimenter that they would earn $10 if they matched or exceeded their performance from the first handgrip endurance trial on the trial they were about to attempt. Participants in the no incentive conditions received no offer of incentive from the experimenter. Participants then completed the second handgrip endurance trial and provided a posttask RPE. Upon completion of the experiment, all participants were debriefed and given honoraria of $10 for completing the study, while the LCC and HCC incentivized conditions received an additional $10 regardless their Trial 2 performance. Throughout the experimental procedure, there was no verbal/motivational encouragement provided by the experimenter at any time.

Data Analysis

Separate one-way analysis of variance models (ANOVAs) were computed for age, MVPA, trait self-control, and 100% MVC force to assess potential covariates to control for within the main analyses. Separate one-way ANOVAs were also calculated for Trial 1 RPE, Trial 2 RPE, Trial 1 task motivation, and Trial 2 task motivation. To evaluate the effects of cognitive control exertion on mental fatigue, a 5 (time: 2, 4, 6, 8, and 10 min) × 4 (condition) mixed ANOVA was computed with post hoc (Tukey) tests to evaluate significant between-condition effects. A series of separate 5 (time: 2, 4, 6, 8, and 10 min) × 1 (condition) repeated-measures ANOVAs were calculated to evaluate mental fatigue over time for each condition.

For the primary hypothesis evaluating the independent and interactive effects of cognitive control exertion and monetary incentives on handgrip endurance performance, a 2 (HCC/LCC) × 2 (incentive/no incentive) mixed ANCOVA, using Trial 1 handgrip endurance performance as the covariate, was computed to compare means between groups for Trial 2 handgrip endurance performance. Based on the study design, ANCOVA was employed as it increases power in randomized studies (i.e., compared with repeated-measures ANOVA; Van Breukelen, 2006). To test our hypotheses, we computed post hoc focused contrasts between each of the conditions to increase power based on recommendations of Muraven and Slessareva (2003, p. 895). In accordance with American Psychological Association (2010) guidelines, Cohen's (*d*) effect sizes were calculated to examine handgrip performance change from Trial 1 to Trial 2 for each condition with adjustment for correlation between the trial scores (Morris & DeShon, 2002).

To assess the differences in patterns of muscle activation between the groups from Trial 1 to Trial 2, we adapted procedures described by Blanchfield, Hardy, and Marcora (2014, p. 5) to derive individual iso-times based on the endurance time achieved on the shortest trial. Using the shortest trial duration as 100% iso-time permitted time-linked, within-person comparisons of proportional motor unit activation at 0%, 25%, 50%, 75%, and 100% of each participant's performance on their second trial with their corresponding activation in a nonfatigued state during Trial 1. For the EMG amplitude analysis, a 5 (time: 0%, 25%, 50%, 75%, 100% iso-time) × 2 (HCC/LCC) × 2 (incentive/no incentive) mixed ANOVA was computed to compare muscle activation using the proportional EMG amplitude change scores (computed as % of MVC on Trial 2 minus % of MVC on Trial 1) at each iso-time. Estimated effect sizes for all analyses are reported as partial eta squared (η_p^2). Greenhouse–Geisser correction was utilized when sphericity was violated. All statistical analyses were performed using statistical processing software (IBM SPSS v20, Armonk, NY).

Results

Demographics and Potential Covariates

Descriptive statistics for age, sex, MVPA, trait self-control, and 100% MVC force are shown in Table 1. Separate one-way ANOVAs showed no significant between-group differences for age, $F(3, 78) = 1.14$, $p = .34$, $\eta_p^2 = .04$; habitual MVPA, $F(3, 78) = 0.46$, $p = .71$, $\eta_p^2 = .02$; trait self-control, $F(3, 78) = 0.46$, $p = .71$, $\eta_p^2 = .02$; and 100% MVC force, $F(3, 78) = 0.28$, $p = .84$, $\eta_p^2 = .01$, supporting the success of the randomization procedures, and therefore, none of these potential covariates were included in the main analyses.

Intermediary Measures

Ratings of perceived exertion. RPE scores are presented by group and trial in Table 1. Separate one-way ANOVAs showed no significant between-group differences for Trial 1 RPE, $F(3, 78) = 2.63$, $p = .06$, $\eta_p^2 = .09$, or Trial 2 RPE, $F(3, 78) = 1.49$, $p = .22$, $\eta_p^2 = .05$.

Mental fatigue. Mental fatigue scores recorded during the experimental manipulation are presented by group over time in Figure 1. A 5 (time: 2, 4, 6, 8, and 10 min) × 4 (condition) mixed ANOVA revealed significant main effects of Time, $F(2.62, 201.37) = 27.23$, $p < .001$, $\eta_p^2 = .26$, and Condition, $F(3, 77) = 37.84$, $p < .001$, $\eta_p^2 = .60$, as well as a significant Time × Condition interaction, $F(7.85, 201.37) = 5.48$, $p < .001$, $\eta_p^2 = .17$. To decompose the between-condition effects, post hoc (Tukey) tests were computed. Results revealed that the two LCC conditions reported significantly less mental fatigue than the HCC conditions (all $ps < .001$). The two LCC groups did not differ from each other, nor did the two HCC groups (all $ps > .40$). Separate repeated-measures ANOVAs were computed for each condition to evaluate changes in mental fatigue scores over time. Results showed significant linear increases in mental fatigue over time in the HCC group, $F(1.85, 35.20) = 8.04$, $p = .002$, $\eta_p^2 = .30$, and the HCC/incentive group, $F(2.03, 38.49) = 22.00$, $p < .001$, $\eta_p^2 = .54$. The effects in the LCC group over time were not significant, $F(4, 76) = 0.55$, $p = .70$, $\eta_p^2 = .03$; however, the LCC/incentive group demonstrated a significant effect, $F(1.62, 32.34) = 7.82$, $p = .003$, $\eta_p^2 = .28$. Thus, although the LCC/incentive group demonstrated a significant increase in mental fatigue over the 10-min experimental manipulation window, the average score during the task was 21/100, whereas both HCC groups averaged over 60/100 indicating mental

Table 1 Age, Sex, MVPA, Trait Self-Control, MVC Force, Trial 1 RPE, Trial 2 RPE, Trial 1 Task Motivation, and Trial 2 Task Motivation by Condition

	LCC	HCC	LCC + $	HCC + $
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
Age (years)	20.14 (1.62)	19.60 (1.54)	19.90 (1.58)	20.45 (1.28)
Sex (*n* male)	7 (33.3%)	8 (40.0%)	8 (38.1%)	7 (35.0%)
MVPA (min/week)	341.90 (204.37)	405.75 (233.06)	342.62 (209.06)	343.50 (188.90)
Trait self-control	3.58 (0.60)	3.54 (0.63)	3.37 (0.66)	3.41 (0.64)
100% MVC (N)	347.79 (113.72)	353.30 (117.17)	375.19 (110.66)	352.41 (79.83)
RPE Trial 1	6.33 (2.13)	6.09 (2.34)	7.33 (2.23)	7.70 (1.87)
RPE Trial 2	7.33 (2.33)	6.83 (2.23)	8.14 (2.10)	7.80 (1.74)
Motivation Trial 1	70.76 (22.70)	77.00 (14.37)	70.67 (17.57)	79.35 (18.80)
Motivation Trial 2	69.62 (24.50)	70.40 (21.49)	65.81 (21.81)	71.30 (19.11)

Note. MVPA = moderate-to-vigorous physical activity; MVC = maximum voluntary contraction; RPE = rating of perceived exertion; N = newton; LCC = low cognitive control/no incentive ($n = 21$); HCC = high cognitive control/no incentive ($n = 20$); LCC + $ = low cognitive control/incentive ($n = 21$); HCC + $ = high cognitive control/incentive ($n = 20$).

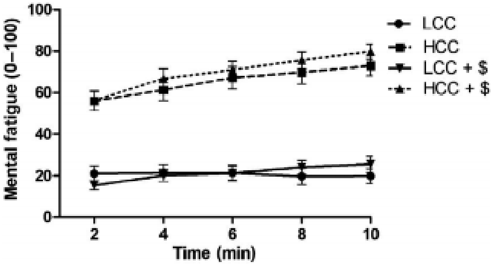


Figure 1 — Mental fatigue over time by condition. Bars represent standard error. HCC = high cognitive control; LCC = low cognitive control; LCC + $ = low cognitive control/incentive; HCC + $ = high cognitive control/incentive.

fatigue was sustained at a much greater level in the HCC groups.

Task motivation. One-way ANOVAs showed no significant between-group differences in motivation to perform the first handgrip task, $F(3, 78) = 1.15$, $p = .34$, $\eta_p^2 = .04$, or the second handgrip task, $F(3, 78) = 0.25$, $p = .86$, $\eta_p^2 = .01$ (see Table 1).

Main Analyses

Physical performance. Change in handgrip endurance performance from Trial 1 to Trial 2 is presented, by condition, in Figure 2. A 2 (HCC/LCC) × 2 (incentive/no incentive) mixed ANCOVA of the Trial 2 handgrip endurance performance scores (time to failure), using Trial 1 performance as a covariate, revealed a significant main effect for Incentive, $F(1, 77) = 7.34$, $p = .008$, $\eta_p^2 = .09$, and a nonsignificant trend for Cognitive Control, $F(1, 77) = 3.56$, $p = .06$, $\eta_p^2 = .04$. The Cognitive Control × Incentive interaction was not significant, $F(1, 77) = 1.13$, $p = .29$, $\eta_p^2 = .02$. Following techniques used by Muraven and Slessareva (2003), to decompose the main effect for Incentive and nonsignificant trend for Fatigue and also to increase statistical power, post hoc focused contrasts were computed. Results of the contrasts revealed significant differences between: the HCC/no incentive and LCC/no incentive conditions, $F(1, 38) = 7.90$, $p = .008$, $\eta_p^2 = .17$; the HCC/no incentive and HCC/incentive conditions, $F(1, 37) = 7.29$, $p = .01$, $\eta_p^2 = .17$; and the HCC/no incentive and LCC/incentive conditions, $F(1, 38) = 10.64$, $p = .002$, $\eta_p^2 = .22$. The contrasts between the LCC/no incentive and LCC/incentive groups, $F(1, 39) = 1.27$, $p = .27$, $\eta_p^2 = .03$, LCC/no incentive and HCC/incentive groups, $F(1, 38) = 0.42$, $p = .52$, $\eta_p^2 = .01$, and the HCC/incentive and LCC/incentive conditions, $F(1, 38) = 0.26$, $p = .61$, $\eta_p^2 = .01$, were not significant.

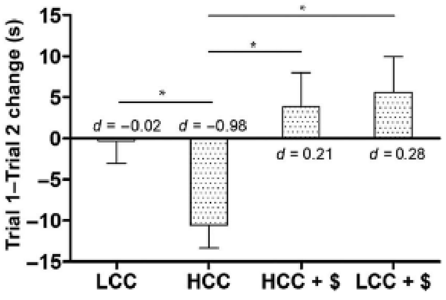


Figure 2 — Handgrip endurance performance change by condition. Effect sizes (Cohen's *d*) represent within-group changes in endurance duration. *Significant ($p < .05$) between-group difference. Bars represent standard error. HCC = high cognitive control; LCC = low cognitive control; LCC + $ = low cognitive control/incentive; HCC + $ = high cognitive control/incentive.

Proportional EMG amplitude. The change in proportional EMG amplitude is shown as a percent difference score from Trial 1 to Trial 2 (where Trial 1 score is represented by "0," or no change) by condition and iso-time in Figure 3. Results of the 5 (0%, 25%, 50%, 75%, and 100% iso-time) × 2 (HCC/LCC) × 2 (incentive/no incentive) mixed ANOVA revealed a significant main effect of iso-time, $F(3.21, 250.38) = 4.15$, $p = .006$, $\eta_p^2 = .05$, and a significant Time × Cognitive Control interaction, $F(3.21, 250.38) = 2.95$, $p = .03$, $\eta_p^2 = .04$. Decomposing the interaction effect by examining differences between conditions at each iso-time point showed no significant differences at 0%, 25%, 50%, and 75% iso-time (all $ps > .05$). However, a significant effect was revealed at 100% iso-time, $F(3, 78) = 3.05$, $p = .03$, $\eta_p^2 = .11$. Post hoc focused contrasts revealed significant differences between the HCC/no incentive and LCC/no incentive conditions ($p = .01$) and the HCC/no incentive and HCC/incentive conditions ($p = .01$). All other main effects and interactions were not significant: Cognitive

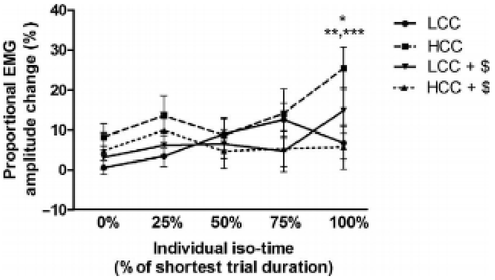


Figure 3 — Trial 1–Trial 2 proportional EMG amplitude change (%) over percent of individual iso-time by condition. *Significant ($p < .05$) Time × Fatigue interaction. **Significant ($p < .05$) difference between HCC and LCC. ***Significant ($p < .05$) difference between HCC and HCC + $. Bars represent standard error. HCC = high cognitive control; LCC = low cognitive control; LCC + $ = low cognitive control/incentive; HCC + $ = high cognitive control/incentive.

Control, $F(1, 78) = 1.76$, $p = .19$, $\eta_p^2 = .02$; Incentive, $F(1, 78) = 1.30$, $p = .26$, $\eta_p^2 = .02$; Time × Incentive, $F(3.21, 250.38) = 1.15$, $p = .33$, $\eta_p^2 = .02$; Cognitive Control × Incentive, $F(1, 78) = 1.03$, $p = .31$, $\eta_p^2 = .01$; Time × Cognitive Control × Incentive, $F(3.21, 250.38) = 1.01$, $p = .40$, $\eta_p^2 = .01$.

Discussion

The main purpose of this study was to investigate the effect of monetary incentives on physical endurance performance following exposure to a mentally fatiguing, HCC task, while also investigating corresponding physiological responses (i.e., motor unit activation) during performance. Consistent with prior research, HCC exertion led to increased perceptions of mental fatigue and was associated with impaired physical endurance performance on the endurance handgrip task with a large effect size ($d = -0.98$). However, as predicted, performance impairments were not observed in the HCC group that was offered a monetary performance-based incentive. Indeed, promise of an incentive led to small positive effects on performance in both the LCC ($d = 0.28$) and HCC ($d = 0.21$) conditions, which did not differ significantly from the trivial effect in LCC group ($d = -0.02$) that was not promised a performance incentive.

The secondary purpose was to investigate the effects of mental fatigue and incentives on muscle activation (i.e., EMG amplitude) during physical endurance performance. Results showed a significant Cognitive Control × Time interaction; however, examination of Figure 3 and post hoc analyses suggest that this effect was largely driven by the greater EMG amplitude seen in the HCC/no incentive condition, and the effects were most pronounced (and significantly different) at the end of the trial when compared with the LCC/no incentive and HCC/incentive conditions. Collectively, results show the deleterious behavioral and physiological aftereffects of mental fatigue can be overcome by offering performance-contingent incentives, resulting in similar neuromuscular adaptations to controls exposed to a LCC task.

Our behavioral results demonstrated an approximate 10-s reduction in isometric handgrip endurance following a 10-min mentally fatiguing task, which equated to a large effect size ($d = -0.98$), and are consistent with a growing body of literature demonstrating a negative carryover effect of mental fatigue on physical performance (Van Cutsem et al., 2017). However, the present findings provide the first evidence that offering a performance-contingent monetary incentive negates physical performance impairments that are typically seen following performance of mentally fatiguing tasks. These results support the effects seen in prior studies where monetary incentives attenuated ego-depletion effects for cognitive tasks involving self-control (Luethi et al., 2016; Muraven & Slessareva, 2003), which suggests that performance on tasks requiring sustained volitional effort can be manipulated by incentives regardless of whether those tasks are cognitive or physical.

Offering a financial incentive to participants reversed the performance decrements typically brought on by mental fatigue. However, incentives did not have a significant effect on performance in the LCC conditions. Specifically, the difference in performance between the two HCC groups was 14 s, whereas the LCC groups differed by only 5 s. It is interesting to note that incentives also did not lead to performance increases in the LCC or control conditions in previous self-control studies (Luethi et al., 2016; Muraven & Slessareva, 2003), which suggests that the motivational salience of an incentive may be enhanced when people are mentally fatigued or ego depleted. Results from Luethi et al.'s (2016) neurological scans suggest that it is also possible that brains of mentally fatigued individuals may be hypersensitive to reward stimuli (i.e., money), which is also consistent with studies showing spontaneous exposure to positive emotional stimuli (Tice, Baumeister, Shmueli, & Muraven, 2007) or glucose-sweetened beverages (e.g., Gailliot et al., 2007; Hagger & Chatzisarantis, 2013) can attenuate self-control depletion aftereffects. Future research should further investigate motivational and neurological factors that may explain how incentives lead to conditions that enable people to overcome or avoid the carryover effects of mental fatigue on physical performance. As one example, studies that have examined the effects of incentives have all utilized only a single level of incentive; thus, it would be interesting to determine if responses to lesser and greater rewards followed a dose–response gradient.

Although the present study did not investigate central nervous system activation, it did allow some insights to physiological factors that may account for people's enhanced physical capabilities when they are mentally fatigued and incentivized to perform. Specifically, our results show increased EMG amplitude during the Trial 2 isometric contraction in the HCC compared with the LCC group. Similar findings have been documented by Bray et al. (2008) and Graham, Sonne, and Bray (2014). From a motor control standpoint, these differences in amplitude suggest that the cortical discharge to the spinal nerves innervating the motor units of the forearm flexors is altered when people are in a state of mental fatigue. As noted earlier, greater EMG amplitude during a submaximal handgrip contraction may be indicative of several phenomena. Given the magnitude of the force generation required by the handgrip task was the same for both performance trials, one trial should not require additional motor unit recruitment unless the cortex is signaling to recruit motor units in a manner consistent with the muscles being fatigued. Greater EMG amplitude in the nonincentivized HCC condition could mean: (a) more/larger motor units are being recruited early in the contraction (i.e., rather than following the size principle; Henneman, Somjen, & Carpenter, 1965); (b) motor units are being recruited in a less synchronized pattern; or (c) stronger cocontraction of antagonist muscles may be occurring, which is causing greater activation of the agonist muscle. However, based on the data from this investigation, it is not possible to conclude which of these (or other) factors is responsible for the increased EMG amplitude in the HCC group.

Although the increased EMG amplitude shown in the HCC group that was not offered an incentive is of interest, the attenuation of the effect in the HCC group that was offered an incentive is also intriguing. Incentives have been shown to increase activation within the brain regions (anterior cingulate cortex) responsible for effortful control (Luethi et al., 2016), which may, in turn, restore "normal" signaling to the motor cortex to recruit motor units in a manner consistent with a rested state. It is also interesting to observe the differences in EMG amplitude between the two HCC groups insofar as the patterns shadow each other during the first half of the trial and then diverge with the HCC/incentive group dropping off in amplitude despite sustaining their contraction significantly longer than the HCC/no incentive group. In these regards, it is noteworthy that people often enable themselves to perform when they are fatigued by altering their performance strategies. For example, studies have shown that depleted/fatigued participants alter their strategies for their performance using mental heuristics (Pohl, Erdfelder, Hilbig, Liebke, & Stahlberg, 2013). Essentially, such strategies are used to "cheat" on the task. Thus, when incentivized to perform, people may adjust their behavior, which could involve utilizing secondary muscle groups to generate compensatory force in support of the primary muscles. Studies from ergonomics have shown this type of "load sharing" occurs among forearm muscles when the muscles become fatigued (e.g., Lucidi & Lehman, 1992). Therefore, sustaining the handgrip squeeze may have relied less on activation of the primary handgrip flexor (i.e., flexor carpi radialis) through a functional reorganization of the motor recruitment patterns to involve supplementary flexor muscles (e.g., flexor carpi ulnaris muscle). Because muscle activation was being recorded using EMG electrodes placed on the flexor carpi radialis and there is limited recruitment territory of ~25 mm with surface electrodes (Yung & Wells, 2013), our EMG recordings would not have detected the contribution of the supplementary musculature. Future research should investigate conscious or unconscious behavioral strategies that may be implemented depending on people's levels of self-regulatory or mental fatigue and incentives and also utilize high-density electrode arrays to assess the spatial distribution of muscle activation under these conditions.

Despite novel findings, the current study is not without limitations. First, monetary incentives may be an impractical intervention due to the associated costs if implemented on a large scale. Furthermore, extrinsic rewards can undermine intrinsic motivation (Deci, Koestner, & Ryan, 1999). As a result, incentivizing performance may deter individuals from enacting self-regulation due to intrinsic factors, such as enjoyment and satisfaction. Second, task motivation was measured prior to offering the monetary incentive, which limits our ability to determine the effect of the incentive on task motivation. However, all conditions reported relatively high motivation (i.e., ~70/100) prior to the incentive manipulation, which parallels previous findings within the literature (e.g., Marcora et al., 2009).

Another limitation relates to the use of isometric handgrip squeezing as a performance measure. Although endurance handgrip squeezing involves maximum voluntary effort akin to the requirements of endurance and strength sports/exercises, the isometric handgrip endurance task lacks ecological validity as an exercise or sport performance task. Despite these concerns, employing endurance handgrip exercise permitted examination of theory-guided hypotheses and motor unit activation patterns using a highly controlled dependent variable with strong internal validity. Moving forward, future research is warranted to test whether monetary incentives facilitate performance under conditions of mental fatigue or HCC exertion among more common sport and exercise contexts, such as cycling and running.

Finally, additional limitations must be acknowledged regarding the study design and HCC experimental manipulation. Employing a single-blind design can introduce the risk that participants' performances are influenced by their interaction with the researcher (e.g., experimenter's bias; Rosenthal, 1964). Double-blind designs have important advantages for reducing bias in experiments; however, these are seldom used in the ego-depletion literature due to the experimenter's role in administering the procedures for the respective experimental manipulations. To address this limitation within the current study, the experimenter followed a script that ensured they did not provide any verbal or motivational encouragement at any time. Another issue that arises, with regard to the HCC task, is the current study employed a Stroop task, which included the color "red" among the word color stimuli. Recent research has shown that exposure to the color or printed text "red" had a negative effect on subsequent task performance among depleted participants (Bertrams, Baumeister, Englert, & Furley, 2015). Although we cannot rule out that the color "red" may have contributed to the negative effects witnessed for participants in the HCC/no incentive group, both the incentive and no incentive conditions that completed the Stroop task were exposed to the same manipulation. Therefore, any effect associated with the color or word "red" could not have influenced difference in performance observed between those conditions.

In conclusion, results support previous findings showing mental fatigue associated with HCC exertion leads to physical performance impairments and muscle activation patterns reflective of fatigue. Findings extend our current understanding by showing that offering monetary incentives can attenuate the deleterious aftereffects of HCC exertion, resulting in similar physical performance and neuromuscular adaptations as seen among people exposed to a LCC exertion task. Future research should further investigate neurological factors that may explain how mental fatigue impairs physical performance and how incentivizing performance enables people to overcome or avoid the negative carryover effects of mental fatigue on physical performance.

References

American Psychological Association. (2010). *Publication manual of the American Psychological Association* (6th ed.). Washington, DC: Author.

Baumeister, R.F. (2014). Self-regulation, ego depletion, and inhibition. *Neuropsychologia, 65*, 313–319. PubMed doi:10.1016/j.neuropsychologia.2014.08.012

Baumeister, R.F., Heatherton, T.F., & Tice, D.M. (1994). *Losing control: How and why people fail at self-regulation*. San Diego, CA: Academic Press.

Baumeister, R.F., & Vohs, K.D. (2016). Strength model of self-regulation as limited resource: Assessment, controversies, update. *Advances in Experimental Social Psychology, 54*, 67–127. doi:10.1016/bs.aesp.2016.04.001

Baumeister, R.F., Vohs, K.D., & Tice, D.M. (2007). The strength model of self-control. *Current Directions in Psychological Science, 16*, 351–355. doi:10.1111/j.1467-8721.2007.00534.x

Beedie, C.J., & Lane, A.M. (2012). The role of glucose in self-control: Another look at the evidence and an alternative conceptualization. *Personality and Social Psychology Review, 16*, 143–153. PubMed doi:10.1177/1088868311419817

Bertrams, A., Baumeister, R.F., Englert, C., & Furley, P. (2015). Ego depletion in color priming research: Self-control strength moderates the detrimental effect of red on cognitive test performance. *Personality and Social Psychology Bulletin, 41*, 311–322. PubMed doi:10.1177/0146167214564968

Blanchfield, A., Hardy, J., & Marcora, S. (2014). Non-conscious visual cues related to affect and action alter perception of effort and endurance performance. *Frontiers in Human Neuroscience, 8*, 967. PubMed doi:10.3389/fnhum.2014.00967

Booth, M.L., Ainsworth, B.E., Pratt, M., Ekelund, U., Yngve, A., Sallis, J.F., & Oja, P. (2003). International physical activity questionnaire: 12-country reliability and validity. *Medicine & Science in Sports & Exercise, 35*, 1381–1395. doi:10.1249/01.mss.0000078924.61453.fb

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Botvinick, M., & Braver, T. (2015). Motivation and cognitive control: From behavior to neural mechanism. *Annual Review of Psychology, 66*, 83–116. PubMed doi:10.1146/annurev-psych-010814-015044

Bray, S.R., Martin Ginis, K.A., Hicks, A.L., & Woodgate, J. (2008). Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology, 45*, 337–343. PubMed doi:10.1111/j.1469-8986.2007.00625.x

Brown, D.M.Y., & Bray, S.R. (2017). Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance. *Sport, Exercise, and Performance Psychology. 6*, 355–369. doi:10.1037/spy0000091

Carter, E.C., Kofler, L.M., Forster, D.E., & McCullough, M.E. (2015). A series of meta-analytic tests of the depletion effect: Self-control does not seem to rely on a limited resource. *Journal of Experimental Psychology: General, 144*, 796–815. PubMed doi:10.1037/xge0000083

Clarkson, J.J., Otto, A.S., Hassey, R., & Hirt, E.R. (2016). Perceived mental fatigue and self-control. In E.R. Hirt, J.J. Clarkson, & L. Jia (Eds.), *Self-regulation and ego control* (pp. 185–202). New York, NY: Academic Press. doi:10.1016/b978-0-12-801850-7.00010-x

Cunningham, M.R., & Baumeister, R.F. (2016). How to make nothing out of something: Analyses of the impact of study sampling and statistical interpretation in misleading meta-analytic conclusions. *Frontiers in Psychology, 7*, 1639. PubMed doi:10.3389/fpsyg.2014.00823

Deci, E.L., Koestner, R., & Ryan, R.M. (1999). A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation. *Psychological Bulletin, 125*, 627–688. PubMed doi:10.1037/0033-2909.125.6.627

de Ridder, D.T., Lensvelt-Mulders, G., Finkenauer, C., Stok, F.M., & Baumeister, R.F. (2012). Taking stock of self-control: A meta-analysis of how trait self-control relates to a wide range of behaviors. *Personality and Social Psychology Review, 16*, 76–99. PubMed doi:10.1177/1088868311418749

Dorris, D.C., Power, D.A., & Kenefick, E. (2012). Investigating the effects of ego depletion on physical exercise routines of athletes. *Psychology of Sport and Exercise, 13*, 118–125. doi:10.1016/j.psychsport.2011.10.004

Englert, C. (2016). The strength model of self-control in sport and exercise psychology. *Frontiers in Psychology, 7*, 314. PubMed doi:10.3389/fpsyg.2016.00314

Englert, C., & Wolff, W. (2015). Ego depletion and persistent performance in a cycling task. *International Journal of Sport Psychology, 6*, 137–151.

Farina, D., Merletti, R., & Enoka, R.M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology, 96*, 1486–1495. PubMed doi:10.1152/japplphysiol.01070.2003

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*, 1149–1160. PubMed doi:10.3758/brm.41.4.1149

Fothergill, A., Attenborough, D., & Fenton, G. (2007). *Planet Earth: Fresh water*. London, UK: BBC Video.

Friese, M., Binder, J., Luechinger, R., Boesiger, P., & Rasch, B. (2013). Suppressing emotions impairs subsequent Stroop performance and reduces prefrontal brain activation. *PLoS ONE, 8*, e60385. PubMed doi:10.1371/journal.pone.0060385

Gailliot, M.T., & Baumeister, R.F. (2007). The physiology of willpower: Linking blood glucose to self-control. *Personality and Social Psychology Review, 11*, 303–327. PubMed doi:10.1177/1088868307303030

Gailliot, M.T., Baumeister, R.F., DeWall, C.N., Maner, J.K., Plant, E.A., Tice, D.M., … Schmeichel, B.J. (2007). Self-control relies on glucose as a limited energy source: Willpower is more than a metaphor. *Journal of Personality and Social Psychology, 92*, 325–336. PubMed doi:10.1037/0022-3514.92.2.325

Graham, J.D., & Bray, S.R. (2015). Self-control strength depletion reduces self-efficacy and impairs exercise performance. *Journal of Sport & Exercise Psychology, 37*, 477–488. PubMed doi:10.1123/jsep.2015-0064

Graham, J.D., Bray, S.R., & Martin Ginis, K.A. (2014). "Pay the piper": It helps initially, but motivation takes a toll on self-control. *Psychology of Sport and Exercise, 15*, 89–96. doi:10.1016/j.psychsport.2013.09.007

Graham, J.D., Martin Ginis, K.A., & Bray, S.R. (2017). Exertion of self-control increases fatigue, reduces task self-efficacy, and impairs performance of resistance exercise. *Sport, Exercise, and Performance Psychology, 6*, 70–88. doi:10.1037/spy0000074

Graham, J.D., Sonne, M.W., & Bray, S.R. (2014). It wears me out just imagining it! Mental imagery leads to muscle fatigue and diminished performance of isometric exercise. *Biological Psychology, 103*, 1–6. PubMed doi:10.1016/j.biopsycho.2014.07.018

Hagger, M.S., & Chatzisarantis, N.L. (2013). The sweet taste of success: The presence of glucose in the oral cavity moderates the depletion of self-control resources. *Personality and Social Psychology Bulletin, 39*, 28–42. PubMed doi:10.1177/0146167212459912

Hagger, M.S., Chatzisarantis, N.L., Alberts, H., Anggono, C.O., Batailler, C., Birt, A.R., … Calvillo, D.P. (2016). A multilab preregistered replication of the ego-depletion effect. *Perspectives on Psychological Science, 11*, 546–573. PubMed doi:10.1177/1745691616652873

Hagger, M.S., Wood, C., Stiff, C., & Chatzisarantis, N.L. (2010). Ego depletion and the strength model of self-control: A meta-analysis. *Psychological Bulletin, 136*, 495–525. PubMed doi:10.1037/a0019486

Heckman, C.J., & Enoka, R.M. (2012). Motor unit. *Comprehensive Physiology, 2*, 2629–2682. PubMed doi:10.1002/cphy.c100087

Henneman, E., Somjen, G., & Carpenter, D.O. (1965). Functional significance of cell size in spinal motoneurons. *Journal of Neurophysiology, 28*, 560–580. PubMed

Hockey, R. (2013). *The psychology of fatigue: Work, effort and control*. London, UK: Cambridge University Press.

Inzlicht, M., Bartholow, B.D., & Hirsh, J.B. (2015). Emotional foundations of cognitive control. *Trends in Cognitive Sciences, 19*, 126–132. PubMed doi:10.1016/j.tics.2015.01.004

Inzlicht, M., Gervais, W., & Berkman, E. (2015, September 12). Bias-correction techniques alone cannot determine whether ego depletion is different from zero: Commentary on Carter, Kofler, Forster, & McCullough, 2015. Retrieved from https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2659409

Inzlicht, M., & Schmeichel, B.J. (2012). What is ego depletion? Toward a mechanistic revision of the resource model of self-control. *Perspectives on Psychological Science, 7*, 450–463. PubMed doi:10.1177/1745691612454134

Ishii, A., Karasuyama, T., Kikuchi, T., Tanaka, M., Yamano, E., & Watanabe, Y. (2015). The neural mechanisms of re-experiencing mental fatigue sensation: A magnetoencephalography study. *PLoS ONE, 10*, e0122455. PubMed doi:10.1371/journal.pone.0122455

Legault, L., & Inzlicht, M. (2013). Self-determination, self-regulation, and the brain: Autonomy improves performance by enhancing neuroaffective responsiveness to self-regulation failure. *Journal of Personality and Social Psychology, 105*, 123–138. PubMed doi:10.1037/a0030426

Lucidi, C.A., & Lehman, S.L. (1992). Adaptation to fatigue of long duration in human wrist movements. *Journal of Applied Physiology, 73*, 2596–2603. PubMed doi:10.1016/0021-9290(85)90243-x

Luethi, M.S., Friese, M., Binder, J., Boesiger, P., Luechinger, R., & Rasch, B. (2016). Motivational incentives lead to a strong increase in lateral prefrontal activity after self-control exertion. *Social Cognitive and Affective Neuroscience, 11*, 1618–1626. PubMed doi:10.1093/scan/nsw073

Lurquin, J.H., & Miyake, A. (2017). Challenges to ego-depletion research go beyond the replication crisis: A need for tackling the conceptual crisis. *Frontiers in Psychology, 8*, 568. PubMed doi:10.3389/fpsyg.2017.00568

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive fatigue effects on physical performance during running. *Journal of Sport & Exercise Psychology, 36*, 375–381. PubMed doi:10.1123/jsep.2013-0249

Marcora, S.M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology, 106*, 857–864. PubMed doi:10.1152/japplphysiol.91324.2008

Mischel, W., Cantor, N., & Feldman, S. (1996). Goal-directed self-regulation. In E.T. Higgins & A.W. Kruglanski (Eds.), *Social psychology: Handbook of basic principles* (pp. 329–360). New York, NY: Guilford Press.

Moller, A.C., Deci, E.L., & Ryan, R.M. (2006). Choice and ego depletion: The moderating role of autonomy. *Personality and Social Psychology Bulletin, 32*, 1024–1036. PubMed doi:10.1177/0146167206288008

Morris, S.B., & DeShon, R.P. (2002). Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological Methods, 7*, 105–125. PubMed doi:10.1037//1082-989x.7.1.105

Muraven, M., & Baumeister, R.F. (2000). Self-regulation and depletion of limited resources: Does self-control resemble a muscle? *Psychological Bulletin, 126*, 247–259. PubMed doi:10.1037/0033-2909.126.2.247

Muraven, M., Shmueli, D., & Burkley, E. (2006). Conserving self-control strength. *Journal of Personality and Social Psychology, 91*, 524–537. PubMed doi:10.1037/0022-3514.91.3.524

Muraven, M., & Slessareva, E. (2003). Mechanisms of self-control failure: Motivation and limited resources. *Personality and Social Psychology Bulletin, 29*, 894–906. PubMed doi:10.1177/0146167203029007008

Pageaux, B., Lepers, R., Dietz, K.C., & Marcora, S.M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *European Journal of Applied Physiology, 114*, 1095–1105. PubMed doi:10.1007/s00421-014-2838-5

Pageaux, B., Marcora, S.M., Rozand, V., & Lepers, R. (2015). Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. *Frontiers in Human Neuroscience, 9*, 67. doi:10.3389/fnhum.2015.00067

Persson, J., Larsson, A., & Reuter-Lorenz, P.A. (2013). Imaging fatigue of interference control reveals the neural basis of executive resource depletion. *Journal of Cognitive Neuroscience, 25*, 338–351. PubMed doi:10.1162/jocn_a_00321

Pohl, R.F., Erdfelder, E., Hilbig, B.E., Liebke, L., & Stahlberg, D. (2013). Effort reduction after self-control depletion: The role of cognitive resources in use of simple heuristics. *Journal of Cognitive Psychology, 25*, 267–276. doi:10.1080/20445911.2012.758101

Rosenthal, R. (1964). The effect of the experimenter on the results of psychological research. *Bulletin of the Maritime Psychological Association, 13*, 1–39.

Segerstrom, S.C., Smith, T.W., & Eisenlohr-Moul, T.A. (2011). The body and self-regulation. In K.M. Sheldon, T.D. Kashdan, & M.F. Steger (Eds.), *Designing positive psychology: Taking stock and moving forward*. Oxford, UK: Oxford University Press.

Smith, M.R., Coutts, A.J., Merlini, M., Deprez, D., Lenoir, M., & Marcora, S.M. (2016). Mental fatigue impairs soccer-specific physical and technical performance. *Medicine & Science in Sports & Exercise, 48*, 267–276. PubMed doi:10.1249/mss.0000000000000762

Stroop, J.R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology: General, 18*, 643–662. doi:10.1037/h0054651

Tangney, J.P., Baumeister, R.F., & Boone, A.L. (2004). High self-control predicts good adjustment, less pathology, better grades, and interpersonal success. *Journal of Personality, 72*, 271–324. PubMed doi:10.1111/j.0022-3506.2004.00263.x

Thomas, S., Reading, J., & Shephard, R.J. (1992). Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Canadian Journal of Sport Sciences, 17*, 338–345. PubMed

Tice, D.M., Baumeister, R.F., Shmueli, D., & Muraven, M. (2007). Restoring the self: Positive affect helps improve self-regulation following ego depletion. *Journal of Experimental Social Psychology, 43*, 379–384. doi:10.1016/j.jesp.2006.05.007

Van Breukelen, G.J. (2006). ANCOVA versus change from baseline: More power in randomized studies, more bias in nonrandomized studies. *Journal of Clinical Epidemiology, 59*, 920–925. doi:10.1016/j.jclinepi.2006.02.007

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The effects of mental fatigue on physical performance: A systematic review. *Sports Medicine, 47*(8), 1569–1588. PubMed doi:10.1007/s40279-016-0672-0

Wewers, M.E., & Lowe, N.K. (1990). A critical review of visual analogue scales in the measurement of clinical phenomena. *Research in Nursing & Health, 13*, 227–236. PubMed doi:10.1002/nur.4770130405

Wood, C., Magnello, M.E., & Jewell, T. (1990). Measuring vitality. *Journal of the Royal Society of Medicine, 83*, 486–489. PubMed

Yung, M., & Wells, R.P. (2013). Changes in muscle geometry during forearm pronation and supination and their relationships to EMG cross-correlation measures. *Journal of Electromyography and Kinesiology, 23*, 664–672. PubMed doi:10.1016/j.jelekin.2013.01.001

Zering, J.C., Brown, D.M., Graham, J.D., & Bray, S.R. (2017). Cognitive control exertion leads to reductions in peak power output and as well as increased perceived exertion on a graded exercise test to exhaustion. *Journal of Sports Sciences, 35*, 1799–1807. doi:10.1080/02640414.2016.1237777

CHAPTER 4:
Effects of mental fatigue on exercise intentions and behavior

Preamble

Effects of mental fatigue on exercise intentions and behavior is the third study in the dissertation series. This study examined the effect of mental fatigue on exercise performance reflective of current public health guidelines for physical activity in a sample comprised of insufficiently active university students. A secondary objective of this study was to examine whether predicted reductions for intended physical exertion correspond with expected exercise performance impairments.

The following manuscript is currently in press (advance online publication) at the journal *Annals of Behavioral Medicine*. The accepted word version of the manuscript (formatted according to the *Annals of Behavioral Medicine* author guidelines) is included in the dissertation as accepted for publication in *Annals of Behavioral Medicine*. The published version of this article can be found at https://academic.oup.com/abm/advance-article/doi/10.1093/abm/kay052/5050539. *Annals of Behavioral Medicine* is the original place of publication: Brown, D. M. Y. & Bray, S. R. (2018) Effects of mental fatigue on exercise intentions and behavior. *Annals of Behavioral Medicine*. Advance online publication. DOI:10.1093/abm/kay052

The copyright for this manuscript is currently held by Oxford University Press (the publisher for the journal *Annals of Behavioral Medicine*). As stated on the Transfer of Copyright form “You may post the accepted manuscript of the Article (but not the published version itself) onto your own website, your institution’s website and in institutional or subject-based repositories, provided that it is not made publicly available until 12 MONTHS after the online date of publication, and that: (1) you include a link (url) to the version of record on the Journal’s website; (2) the Journal is attributed as the original place of publication with the correct citation details given.” (see Appendix E.3).

Contribution of Study 3 to overall dissertation

Study 3 builds on the findings of Studies 1 and 2 by showing that the effects of mental fatigue extend to exercise behaviour reflective of public health guidelines for health and fitness benefits among a sample representative of the general population. Study 3 replicated the findings of Martin Ginis and Bray (2010) showing that mental fatigue alters the amount of physical effort people are willing to invest in an exercise workout and extends their work by demonstrating that people follow through with those intentions by doing less work and exercising at lower heart rate intensities. Findings suggest intended physical exertion may be a specific motivational process that influences exercise performance. Together, these are the first results showing people may deliberately adjust their physical effort to cope with mental fatigue when performing public health guideline based exercise for health and fitness benefits.

Abstract

Background: Exerting cognitive control results in mental fatigue, which is associated with impaired performance during physical endurance tasks. However, there has been little research on the effects of mental fatigue on people's perceptions or behaviors involving lifestyle or recreational exercise. *Purpose:* The purpose of this study was to examine the effect of mental fatigue on intended physical exertion and exercise performance reflective of current physical activity guidelines. *Methods*: Using a counterbalanced design, participants completed two 50-minute experimental manipulations (high vs. low cognitive control exertion) before exercising at a self-selected intensity for 30 minutes. At Visit 1, participants performed a graded exercise task to gain familiarity with a range of exercise intensities and rating perceived exertion (RPE) while exercising. At Visits 2 and 3, participants rated their intended RPE for the exercise session, performed the experimental manipulations, re-rated their intended RPE, and then completed 30-minutes of exercise on a cycle ergometer. Total work performed while exercising was recorded for each session. *Results*: Compared to the low cognitive control condition, the high cognitive control manipulation resulted in significantly greater mental fatigue (*d* = .73), significantly greater reductions in intended RPE (Mean difference = -0.62) and significantly less total work (-12.7 kJ) performed during the exercise session. *Conclusions*: Mental fatigue alters the amount of physical effort people are willing to invest in an exercise workout and follow through with those intentions by doing less work. These are the first

results showing people may deliberately adjust their physical effort to cope with mental fatigue.

Effects of Mental Fatigue on Exercise Intentions and Behavior

Current public health recommendations are for adults to accumulate at least 150 minutes of moderate-to-vigorous intensity physical activity (MVPA) each week (1,2). However, the vast majority of North Americans fail to meet these guidelines (3,4). The fact that most people do not accumulate enough physical activity is somewhat of a paradox as most are aware of the importance of physical activity (5) and have motivation or intentions to be more active (6,7).

Although data suggest individuals may be motivated to be more active, people experience a number of barriers to physical activity that interfere with the translation of motivation into behavior (8). We hypothesize that for many people, high cognitive control demands of work, school and other daily activities may leave them in a state of mental fatigue that impairs their motivation and abilities to engage in adequate amounts and intensities of physical activity.

Self-control, or self-regulation, involves altering one's habitual or natural responses based on standards or goals (9). For most people, engaging in sufficient levels of physical activity requires self-control insofar as they must plan and deliberately engage in physical activities during discretional/leisure time in place of more rewarding sedentary behaviors (10). Baumeister and Vohs (9) theorize that exerting self-control results in the depletion of an energetic resource, which leads to a lack of volition to exert further self-control due to low energy or fatigue.

Cognitive control is a central aspect of self-control involving mental processes that allow people to override, inhibit, or restrain unwanted, but dominant, behaviours (11). For example, people exert cognitive control when they maintain vigilant attention during a lecture or meeting and suppress the tendency to let their minds wander (12) or when they forego their favorite unhealthy food choices for something that is "better for them" (13). Cognitive control has many benefits and is an essential ingredient for goal-directed behaviour. However, cognitive control requires energy and effort (14), which has implications for how we think, feel and behave after cognitive control has been exerted.

A meta-analysis of the literature on self-control strength depletion by Hagger, Wood, Stiff and Chatzisarantis (15) showed that engaging in an initial task requiring cognitive or self-control led to significant impairments in performance of subsequent tasks that also required self-control with a medium to large effect size (d = .62). Although there has been controversy surrounding the size and direction of the ego depletion effect (16), it should be noted that hundreds of studies have demonstrated the negative carryover effect of prior self-control exertion suggested by Hagger et al.'s (15) meta-analysis. The same meta-analysis showed cognitive control exertion has negative effects (d = -.44) on mental fatigue. Although mental fatigue has been investigated extensively in cognitive science (17), it has received little attention in exercise science or behavioral medicine. This lack of attention is surprising given "fatigue" is a frequently-cited barrier to engaging in physical activity (18).

Over the past decade numerous studies have shown that after people exert cognitive effort on an initial task (e.g., Stroop task), performance on subsequent tasks involving physical effort or motor skill are impaired (19,20). For instance, the negative effects of cognitive control exertion have been seen across a wide range of physical tasks including, isometric handgrip endurance (21), repetitive resistance exercise (22), whole-body cardiovascular endurance exercise (23), VO_{2max} testing (24), and soccer performance (25). However, research to date has primarily focused on performance of highly controlled exercise tasks (e.g., cycling at 80% of maximum power or holding a submaximal handgrip squeeze until exhaustion) that were selected or designed by researchers to test specific hypotheses about the effects of cognitive control or mental fatigue on physical performance as well as potential explanatory mechanisms (e.g., cardiovascular responses, muscle activation). A question that has received little attention is the extent to which cognitive control exertion and its associated mental fatigue may affect motivation and behavior involving the types of physical activities people engage in for health and fitness benefits.

Investigation of the effects of cognitive control or mental fatigue on lifestyle or recreational physical activity may provide important information in terms of understanding why such a large percentage of the population is insufficiently active despite strong intentions to be active. Therefore, research is needed to determine whether cognitive control exertion and mental fatigue have negative effects on exercise behaviors reflective of current public health guidelines.

Research is also needed to better understand how cognitive control exertion or mental fatigue can affect people's motivation towards engaging in physical activity. Inzlicht and Schmeichel (11) proposed an alternative to Baumeister's energy depletion theory, suggesting that because self-control requires effort, exerting cognitive control on one task may cause temporary shifts in motivation away from subsequent tasks that require effort to those that are less effortful. This theorizing has not been supported as several studies have found that people's task motivation is not affected by cognitive control exertion (26,27). However, general measures of task motivation may fail to assess more subtle or specific aspects of motivation that may be affected by prior exertion of cognitive control. For example, people may be equally motivated, but may adjust their approach to the task by deliberately altering how much effort they put into doing it.

In one of the few studies to have investigated the effects of cognitive control exertion on people's exercise motivation, Martin Ginis and Bray (28) examined whether participants’ planned physical exertion for performing a cardiovascular exercise circuit changed after completing a cognitive control (Stroop task) manipulation. In that study, all participants reported their intended physical exertion prior to performing a brief cognitive control exertion manipulation and again afterwards. Participants in the control group, who performed the low cognitive control task (congruent Stroop task), showed no changes in intentions, while those who performed the high cognitive control task (incongruent Stroop task) significantly reduced their intended physical effort (*d* = -.44). Thus, both groups of participants were motivated to engage in the task; however, intention to exert physical effort was negatively affected after exerting high cognitive control. As this is the only study to have examined the effects of cognitive control exertion on exercise intentions, further research is needed to determine if these effects are reproducible. Additional research is also needed to ascertain whether the effects of cognitive control exertion on intentions lead to corresponding changes in behavior, as behavior was not assessed in that study.

The purpose of the present study was to investigate the effect of cognitive control exertion on mental fatigue and exercise-related perceptions and behavior reflective of current public health physical activity guidelines (i.e., MVPA). We hypothesized that, compared to a low cognitive control manipulation, engaging in a 50-minute high cognitive control task would a) cause increases in mental fatigue, b) reduce intended physical exertion for a 30-minute exercise session and c) decrease the amount of total work performed during a 30-minute exercise session.

Method

Participants and Design

Participants were twenty-five university students (13 males, 12 females) with a mean age of 20.16 (*SD* = 1.48) and a mean body mass index of 22.76 (*SD* = 3.54). Inclusion criteria specified participants must not have achieved the current American College of Sports Medicine (ACSM; 29) physical activity recommendations of ≥150 minutes of MVPA per week in the past 6 months, which was confirmed by self-reported weekly MVPA (*M* = 92.13 ± 44.24 minutes). Prior to study participation all participants were screened for contra-indicators of performing moderate-vigorous intensity exercise using the Physical Activity Readiness Questionnaire (30) and provided informed consent.

This study employed a within-subject, crossover design. We computed a sample size estimate using G*Power 3.1 (31) based on effect sizes reported by McMorris et al. (32) from studies that examined the effects of the AX-CPT compared to documentary viewing on subsequent physical performance. Specifically, there were two studies that were within-subject crossover designs which demonstrated effect sizes ranging from $g = 0.27$ (26) to $g = 0.33$ (23) with an average effect size of $g = .30$. According to G*Power calculations, for our primary analysis using a two condition, within-group repeated measures ANOVA design with $\beta = .80$ and $\alpha = .05$, 24 participants were required. To account for potential participant attrition, 26 participants were recruited, however, one participant dropped out of the study. On separate visits, participants performed one of two experimental manipulations consisting of either a high cognitive control task or a low cognitive control task after which they engaged in a 30-minute exercise session at a self-determined workload. Participants were instructed to avoid consuming caffeinated beverages or foods prior to testing as well as to get at least 8 hours of devoted rest the night before their study session and confirmed adherence to these requirements prior to each testing session. An institutional research ethics board reviewed and approved the study.

Measures

Demographics, MVPA and anthropometrics. Demographic information for self-reported sex, age as well as average weekly MVPA during the six months prior to the study were obtained for descriptive purposes. The International Physical Activity Questionnaire (33) was used to assess weekly minutes of MVPA during the past 6 months. Anthropometric data included height and weight, which were obtained using a calibrated weigh scale and tape measure, which also provided calculation of body mass index (mass(kg)/height(m)^2).

Graded cardiovascular exercise test (GXT). All participants completed a GXT on a cycle ergometer (Lode Corival, Groningen, The Netherlands). The GXT served two purposes. The first was to educate and acclimate participants to make reliable ratings of perceived exertion (RPE) at exercise workloads of varying resistance. The second was to determine RPE that corresponded with specific workload ranges for each individual, which were then used to set the workloads participants began exercising at during visits 2 and 3. The GXT consisted of a 3-minute warm-up at a light intensity (50W) resistance at a self-determined cadence that was > 50 RPM, after which resistance was automatically increased by 25W every 2 minutes until volitional termination of the test by the participant or the point at which their pedal cadence fell below 50 RPM and could not be increased despite instructions from the experimenter to increase their RPM. Participants provided RPE ratings at 30-sec intervals during the test and upon test completion. The ergometer was set in hyperbolic (rpm-independent) mode to ensure the workload was constant throughout each level of the GXT regardless of pedaling speed.

Process Variables

Heart rate (HR). HR was monitored continuously throughout the 30-minute exercise sessions and the 50-minute experimental manipulations using a Polar heart rate monitor (Polar S625X). HR was represented by the mean values computed over one-minute intervals during the exercise protocols, which were averaged to provide the measure HR_{AVE} for each session. HR was represented by the mean values computed over ten-minute intervals during the experimental manipulations, which were averaged to provide the measure COG-HR_{AVE} for each session.

Primary Outcome Measures

Mental Fatigue. A Visual Analogue Scale (VAS [34]) was used to assess mental fatigue five times during each cognitive control experimental manipulation: after the first 10 minutes of performing the task and at 10-minute intervals thereafter. The mental fatigue VAS has demonstrated strong validity and reliability (35). To complete each measure, 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 'none at all' on the left hand side corresponding with 0 and 'maximal' on the right hand side corresponding with 100. Scores were calculated by measuring the distance (in mm) the 'X' was placed from the left side of the scale. Consistent with Boksem and Topps' (17) conceptual definition of mental fatigue: "the feeling that people may experience after or during prolonged periods of cognitive activity" (p. 125), and previous research (36), mental fatigue was operationalized as the "area under the curve" (Mental Fatigue Area Under Curve) representing the additive or cumulative effect of the cognitive control manipulation on participants' scores for on the five VAS measures as well as the last score reported by participants upon completion of the manipulations (Mental Fatigue Final).

Total work. The amount of accumulated energy (kJ) during the 30-minute exercise sessions served as the indicators of total work. Participants were able to manually adjust the workload on the cycle ergometer using the up/down buttons throughout each cycling session

Intended physical exertion (Intended RPE). Participants rated the level of physical exertion at which they intended to exercise at during the 30-minute exercise session using Borg's 6 (no exertion at all) to 20 (maximal exertion) RPE scale (37). Following the methodology of Martin Ginis and Bray (28), intended RPE was assessed prior to and following each of the experimental manipulations. As per the analysis procedures described by Martin Ginis and Bray (28), the effects of the experimental manipulations on intended RPE were represented as change scores computed by subtracting the pre-manipulation score from the post-manipulation score.

Potential Covariate

Task motivation. To assess task motivation prior to each 30-minute exercise session, a Visual Analogue Scale (34) was employed. 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 instructed to place an ‘X’ at the point along a 100 mm line with the anchors ranging from ‘none at all’ on the left hand side corresponding with 0 and ‘maximal’ on the right hand side corresponding with 100. Scores were calculated by measuring the distance (in mm) that the ‘X’ was placed from the left side of the scale.

Experimental Manipulations

The cognitive control task manipulations were delivered in a structured 52-minute window consisting of five 10-minute blocks each separated by 30-second breaks, in which participants provided ratings of mental fatigue.

High cognitive control (mental fatigue) task. Participants completed the AX-Continuous Performance Test (AX-CPT; 38) for 50 minutes. A longer-duration version of this task (90-minutes) has been used previously to examine the effects of mental fatigue on physical performance (23,39,40). The 50-minute version was used in this study to simulate the time demands of a typical university lecture at the institution attended by the participants. The AX-CPT involves higher order cognitive control and sustained attention. In this task, "cue-probe" sequences consisting of four letters were visually presented one at a time in a continuous fashion on a 17” flat screen computer monitor. Each cue-probe sequence involved presentation of a red cue letter first, followed by two white distractor letters, and finishing with a red probe letter. Participants were instructed to press the left mouse button on target trials and the right mouse button on non-target trials. Target trials occurred with 70% frequency and were defined as a cue-probe sequence in which the letter A appeared first as the cue and the letter X appeared fourth as the probe. Non-target trials occurred with 30% frequency and were represented evenly (10% each) by the following types: BX trials, invalid cue (non-A) preceding a valid probe (X); AW trials, valid cue (A) followed by an invalid probe (non-X); and BW trials, invalid cue (non-A) followed by an invalid probe (non-X). Distractor letters consisted of any letters with the exception of A, K, X, or Y. Letter sequences were presented centrally on a black background on the monitor for 300 ms in 24-point uppercase Helvetica font, followed by a 1,200-ms interval in which the monitor screen was blank. Each trial was 6000-ms in duration, with a 4,500-ms delay between the presentation of the cue and probe stimuli. Participants performed a standard number of practice trials (i.e., 20) for which they had to correctly answer ≥ 80% of trials in order to demonstrate they understood how to correctly perform the task. Following procedures described by Marcora et al. (23), performance was measured as the percentage of correct responses in each 10-minute block.

Low cognitive control task. Participants watched a 50-minute documentary film (41) on a 17” flat screen computer monitor. To ensure attention was engaged throughout the duration of the task, participants were asked to monitor the audio commentary and recorded instances when they heard a key word: "*water*". Similar documentary video manipulations have been used as low cognitive control tasks in other investigations (23,24,40).

Procedure

Participants attended three laboratory sessions. Upon arrival at the laboratory for Session 1, participants completed the Physical Activity Readiness Questionnaire, provided informed consent and completed the demographic and physical activity questionnaires. Participants then had their height and weight recorded, were fitted with a HR monitor, and instructed how to use the RPE scale (following instructions provided by Borg [37]; p. 47). Participants then completed a 3-minute warm-up followed by the GXT and a 3-minute cool-down. During the GXT, participants verbally reported their RPE every 30-seconds, and upon completion of the task. Lastly, participants were scheduled for the second lab visit at approximately the same time of day and no less than 48 hours later to allow for recovery from the GXT and asked to refrain from strenuous exercise during the 24-hour period preceding each of the remaining sessions.

Prior to Sessions 2 and 3, the order in which each participant would complete the experimental manipulations was randomized with 12 completing the high cognitive control manipulation and 13 completing the low cognitive control manipulation during Session 2. Upon arrival at the lab, participants were fitted with a HR monitor. Next, the experimenter read aloud the current ACSM (29) physical activity prescription guidelines for cardiorespiratory exercise. Specifically, participants were instructed that exercise performed at RPEs of 12 to

17 correspond with moderate-to-vigorous exercise intensities, which are necessary to accrue health benefits. Participants then completed the pre-manipulation Intended RPE measure. As per the crossover design, participants then performed one of the two 52-minute cognitive control manipulations. Upon completion of the experimental manipulation, participants completed the Intended RPE measure again and the task motivation measure. Next, participants mounted the cycle ergometer and performed a three-minute warm-up at a fixed resistance of 50W. Following the warm-up, the experimenter adjusted the resistance on the cycle ergometer to the workload corresponding to the participant's Intended RPE (from their GXT session) to provide an initial resistance level and informed participants they were able to adjust the workload as they wished throughout the 30-minute, self-paced, exercise session. Upon completion of the 30-minute exercise session, participants performed a three-minute cool down. After dismounting the cycle ergometer at the end of Session 2, participants scheduled Session 3 at a time no less than 48 hours later. Session 3 followed identical procedures to Session 2, with the exception of performing the alternate cognitive control manipulation to that performed in Session 2. Upon completion of Session 3, participants were debriefed. Throughout the experimental procedure, experimenters interacted with participants to provide instructions, to take measures, and to ensure the safety of participants during the procedure. There was no verbal/motivational encouragement provided by the experimenters at any time. Participants were

remunerated upon completion of each laboratory session ($10 CAD for session 1 and $20 CAD for each of Sessions 2 and 3).

Data Analysis

Descriptive statistics were computed for all study variables and were expressed as Means and Standard Deviation. Analysis of variance models and paired samples *t*-test models are presented as degrees of freedom, test statistic, probability value, and effect size. Bivariate (Pearson's *r*) correlations are presented as correlation coefficient and probability value. For all of the analyses, the effect of experimental manipulation "Order" was modeled as a between groups effect (high cognitive control first/low cognitive control second; low cognitive control first/ high cognitive control second) to evaluate the main effects and the possibility of a differential crossover effect (Condition X Order interaction). A 2 (Condition) X 2 (Order) mixed ANOVA was computed to assess task motivation. A paired samples *t*-test was computed to assess the change in cognitive performance from block 1 to block 5 on the AX-CPT, with reduced performance providing a secondary indictor of mental fatigue. Separate 2 (Condition) X 2 (Order) mixed ANOVAs were computed to evaluate differences for HR during the cognitive control experimental manipulations (COG-HR$_{\text{AVE})}$ and during each 30-minute exercise bout (HR$_{\text{AVE}}$). Results for COG-HR$_{\text{AVE}}$ and HR$_{\text{AVE}}$ are shown Table 1. To evaluate the effect of the cognitive control experimental manipulations on mental fatigue, separate~~a~~ 2 (Condition) X 2 (Order) mixed ANOVAs were computed for Mental Fatigue Area Under Curve and Mental Fatigue Final. Separate bivariate (Pearson) correlations were calculated to examine the relationship between Mental Fatigue Area Under Curve and Mental Fatigue Final for the low and high cognitive control conditions, respectively. For the hypotheses evaluating the effects of cognitive control exertion on Intended RPE (see Figure 1) and total work (see Figure 2), separate 2 (Condition) X 2 (Order) mixed ANOVAs were computed. Estimated effect sizes for all analyses are reported as partial eta squared (η_p^2). Effect sizes (Cohen's *d*) were calculated separately for each main variable with adjustment for within-group correlations between conditions (42) as per the American Psychological Association (43) guidelines. All statistical analyses were performed using IBM SPSS version 20.

Results

Potential Covariate

Task motivation. Task motivation scores were 47.64 (*SD* = 23.49) and 46.00 (*SD* = 19.00) for the high cognitive control and low cognitive control sessions, respectively. A 2 (Condition) X 2 (Order) mixed ANOVA showed no significant effects for Condition, F (1, 23) = .12, p = .74, η_p^2 = .01, Order, F (1, 23) = .05, p = .82, η_p^2 = .01, or the Condition X Order interaction, F (1, 23) = .24, p = .63, η_p^2 = .01, indicating task motivation for the exercise task was high in both conditions and it was not necessary to include task motivation as a covariate in the main analyses.

Experimental Manipulation

COG-HR$_{\text{AVE}}$. Heart rate values during the cognitive manipulations are reported in Table 1. A 2 (Condition) X 2 (Order) mixed ANOVA showed no significant main effects of Condition, F (1, 23) = .45, p = .51, η_p^2 = .02, or Order, F (1, 23) = .08, p = .78, η_p^2 = .00, and a non-significant Condition X Order interaction, F (1, 23) = .07, p = .79, η_p^2 = .00. Overall, these results show there were no differences in physiological arousal associated with the experimental manipulations.

Cognitive performance. A paired samples *t*-test revealed a significant decline in the number of correct responses from the first 10-minute block (M = 96.88 ± 2.42) performing the AX-CPT compared to the final 10-minute block (M = 94.44 ± 5.74), t (24) = 2.01, p = .05, d = .44. These results demonstrated a decline in cognitive performance consistent with greater mental fatigue (44,45).

Heart Rate during Exercise

HR$_{\text{AVE}}$. Heart rate values during the exercise sessions are reported in Table 1. A 2 (Condition) X 2 (Order) mixed ANOVA revealed a significant main effect for Condition, F (1, 23) = 7.40, p = .01, η_p^2 = .25, showing higher HR during exercise following exposure to the low cognitive control condition. The main effect for Order, F (1, 23) = 1.44, p = .24, η_p^2 = .06, and the Condition X Order interaction, F (1, 23) = 3.29, p = .08, η_p^2 = .13, were not significant.

Main Analyses

Mental fatigue. Mental fatigue scores recorded during the experimental manipulations are presented by condition in Table 1. Bivariate (Pearson's r)

correlations revealed very strong positive correlations between Mental Fatigue Area Under Curve and Mental Fatigue Final for the low cognitive control ($r = .95$, $p < .001$) and high cognitive control condition ($r = .94$, $p < .001$). Separate 2 (Condition) X 2 (Order) mixed ANOVAs were computed for Mental Fatigue Area Under Curve and Mental Fatigue Final. Both analyses revealed significant main effects for Condition (all *ps* < .001), whereas the main effects of Order, and Order X Condition interactions did not show significant differences (all *ps* ≥ .20). Overall, results indicate greater mental fatigue in the high cognitive control condition.

Intended RPE. Participants' pre- and post-manipulation ratings of Intended RPE for the exercise sessions are presented, by condition, in Figure 1. A 2 (Condition) X 2 (Order) mixed ANOVA of the change scores revealed a significant main effect for Condition, $F\ (1, 23) = 11.00$, $p = .003$, $\eta_p^2 = .32$, demonstrating a greater reduction in Intended RPE following the high cognitive control manipulation compared to the low cognitive control manipulation. Neither the main effect for Order, $F\ (1, 23) = .04$, $p = .84$, $\eta_p^2 = .00$, or the Condition X Order interaction, $F\ (1, 23) = 1.17$, $p = .29$, $\eta_p^2 = .05$, were significant.

Total work. Accumulated energy (kJ) for the exercise trials are displayed, by condition, in Figure 2. A 2 (Condition) X 2 (Order) mixed ANOVA revealed a lower amount of total work performed in the high cognitive control condition compared to the low cognitive control condition , $F\ (1, 23) = 5.67$, $p = .03$, $\eta_p^2 = .20$. The main effect for Order, $F\ (1, 23) = .25$, $p = .62$, $\eta_p^2 = .01$, and the

Condition X Order interaction, *F* (1, 23) = .20, *p* = .66, $\eta_p^2 = .01$, were not significant.

Discussion

In this study, we examined the effects of a 50-minute task, requiring high levels of cognitive control, on intended physical exertion and total work for a 30-minute self-paced exercise task. Results were consistent with an abundant literature demonstrating high cognitive control exertion results in significant increases in mental fatigue (22,23,36). However, this is the first study to show that mental fatigue also results in a significant reduction in intended RPE for exercise and less accumulated energy while engaging in exercise that aligns with public health guidelines for MVPA.

Population-based studies have revealed that nearly half of adults experience symptoms of fatigue on a daily basis (46-49). In many work and academic environments, people are tasked with performing a variety of activities requiring high levels of cognitive control or mental effort, therefore it is not surprising that fatigue is a common reason for not engaging in physical activity (18).

The present results support the mounting body of evidence showing physical performance is impaired following exposure to mentally fatiguing, cognitive control tasks (19). However, samples in those studies have largely been comprised of trained athletes or highly active participants as well as highly strenuous exercise tasks, often performed to exhaustion (e.g., 23,24). In contrast, our study focused on recreationally-active participants engaging in exercise consistent with ACSM guideline recommendations for MVPA (29). In support of our hypothesis, findings showed that compared to a low cognitive control task, high cognitive control exertion resulted in a significant decrease in total work performed over the course of a 30-minute self-paced, aerobic exercise task. Although ~13 kJ over 30 minutes may seem like a trivial amount, the difference between exercise bouts translates into almost one kilometer in distance traveled (843.74 meters), which at the average work rate performed would have taken approximately two additional minutes to perform in the high cognitive control condition. Furthermore, it is important to consider the decrease in accumulated energy over 30-minutes of MVPA may be extrapolated over multiple exercise sessions engaged in by people when they are mentally fatigued. For example, meeting minimum public health guidelines of 150 minutes of MVPA per week would require five, 30-minute sessions. Thus, a reduction in accumulated energy of 13kJ per session would translate into 65kJ per week (3380kJ / year) and over time, the accumulating reductions in physical performance associated with exercising while mentally-fatigued could have important implications for weight management. Considering the multi-billion dollar health costs and comorbid conditions (e.g., diabetes, hypertension) associated with overweight and obesity (50,51), future research examining the underlying mechanisms impacting physical activity behavior and intervention strategies to cope with mental fatigue appears warranted.

Physiological data associated with decreased accumulated energy also demonstrated an average heart rate of ~8 beats per minute lower following high cognitive control exertion. Despite still being within the ACSM (29) moderate-intensity heart rate target zone, the average reduction in heart rate from 159 beats per minute following the low cognitive control manipulation to 151 beats per minute after the high cognitive control task represents a down-regulation from vigorous to moderate intensity exercise based on the ACSM guidelines. This result may also have important implications for health, considering cardiovascular adaptations are intensity-dependent (52,53). Furthermore, engaging in higher intensity versus lower or moderate-intensity exercise is associated with reduced risk of cardiovascular disease, improved diastolic blood pressure and better glucose control (53). In light of this evidence, failing to achieve higher intensities of exercise due to mental fatigue also risks failing to confer important cardio-protective benefits.

The finding that people down-regulate their self-selected exercise intensity after being mentally fatigued has implications for the public and personal health benefits that may be derived from exercise participation. However, it is also important to note that mental fatigue also down-regulated people's intentions regarding how much exertion they were willing to put into the exercise to be performed. As mentioned earlier, theorists in the area of self-regulation (11,54) have proposed that exerting cognitive control on one task may reduce motivation to exert control on later tasks. Yet, research that has assessed task motivation (including the present study) has failed to detect any motivational shifts consistent with these predictions (26,27). Our findings suggest that measures of task motivation may be too general or abstract to detect the shift in motivation that may occur when people are mentally fatigued and that it may not be the direction of motivation (i.e., the desire to engage in the task) that changes, but motivation captured by the planned intensity at which the task will be performed that is affected by mental fatigue. The decrease in planned intensity then seems to also translate into reductions in total work performed while exercising.

The above interpretation of participants' motivation to exercise when they were mentally fatigued must also be qualified by the constrained parameters involved in the study. That is, participants enrolled in a study that required they engage in physical activity, and therefore may have been highly committed to exercising regardless of the transient motivational consequences of the experimental manipulations. Thus, the extent to which motivation to engage in effortful exercise may also be affected if participants were offered an opportunity to forego exercising is not known. Important questions thus arise regarding the extent to which mental fatigue may alter people's decisions about whether to exercise or not even when they have abundant and accessible opportunities for a brisk walk, jog, or workout at the gym. Future research is necessary to answer these questions.

Given the sample was comprised of university students and the manipulations were designed to be consistent in duration (i.e., 50 minutes) and possess similar basic cognitive characteristics (i.e., sustain attention) of a lecture, the results are relevant to university students who are exposed to lectures, labs and tests of similar duration. Further, although these results show mental fatigue affects exercise intentions and behavior following one 50-minute bout of high cognitive control, students must manage multiple prolonged periods of cognitive effort daily which raises concerns about the extent to which accumulating mental fatigue may have more serious implications for students' physical activity levels. A considerable body of research has shown that physical activity levels decline dramatically during the transition to university (e.g., 55,56) despite students having ready access to recreational facilities and programming. Thus, the present findings may help to explain why university students may struggle to be physically active.

The current study is not without limitations. For instance, the study used a homogenous sample of young, healthy undergraduate students that were not currently active at levels that meet public health recommendations. Therefore, results may not generalize to people who are sedentary, young adults in the workplace, or middle-aged and older adults. A study design limitation that should be acknowledged pertains to employing a single-blind design, which poses potential risk of experimenter bias effects (57). To address this limitation, the experimenter followed a detailed script to ensure all interactions with participants were consistent for each condition.

A further limitation is that perceived exertion was not measured while people were exercising. There is some evidence in the literature that cognitive control exertion leads to significantly higher ratings of perceived exertion when exercising at a fixed workload (e.g., 80% max workload [23]). However, because participants in the present study could adjust the workload on the cycle ergometer to suit their preferred level of exertion while exercising, having them rate their perceived exertion may have been biased due to the fact they had already indicated the level of RPE at which they intended to exercise. An additional limitation relates to the manipulation used to induce mental fatigue. That is, the AX-CPT lacks ecological validity insofar as it is not a cognitively-demanding task people would engage in outside of a contrived laboratory environment. Furthermore, mental fatigue reported by participants in the experimental condition may have also been accompanied by feelings of frustration, boredom or other negative affect that could be associated with that task and may not be characteristic of university lectures. Therefore, it is also possible that the results are partially, or fully attributable to factors that may accompany or operate independently from mental fatigue. Nevertheless, the AX-CPT does have inherent complex cognitive and attentional demands that may be similar to tasks performed in naturalistic school or workplace environments. The present study provides some evidence of the negative effects of mentally-fatiguing tasks on motivation and physical activity; however, future research investigating the effects of real-world cognitive activities on mental fatigue and physical activity are clearly needed.

In conclusion, results show exertion of cognitive control causes significant increases in mental fatigue, which in turn, lead to decreases in intended physical exertion and lower total work performed while completing a 30-minute self-paced exercise task. Results align with previous research, but are the first to indicate cognitive control causes shifts in motivation for intended physical effort and to have utilized an exercise task consistent with public health recommendations for MVPA. Future research is needed to examine how mental fatigue accumulated over longer periods such as an entire work or school day affects physical activity motivation and behavior. Moving forward, research aimed at identifying psychological and physiological processes by which mental fatigue may impede motivation and physical performance is needed to inform the development and evaluation of interventions that may attenuate the negative effects of cognitive control exertion on physical activity motivation and behavior.

References

1. Haskell WL, Lee IM, Pate RR, et al. Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Circulation*. 2007; 116: 1081.
2. Tremblay MS, Warburton DE, Janssen I, et al. New Canadian physical activity guidelines. *Appl Physiol Nutr Metab*. 2011; 36: 36-46.
3. Colley RC, Garriguet D, Janssen I, Craig CL, Clarke J, Tremblay MS. Physical activity of Canadian adults: accelerometer results from the 2007 to 2009 Canadian Health Measures Survey. *Health Rep*. 2011; 22: 7-14.
4. Ward B, Clarke T, Nugent C, Schiller J. *Early release of selected estimates based on data from the 2015 National Health Interview Survey*. National Center for Health Statistics. 2017. Available from: www.cdc.gov/nchs/nhis.htm
5. Martin SB, Morrow Jr JR, Jackson AW, Dunn AL. Variables related to meeting the CDC/ACSM physical activity guidelines. *Med Sci Sport Exer*. 2000; 32: 2087-2092.
6. Godin G, Conner M. Intention-behavior relationship based on epidemiologic indices: an application to physical activity. *Am J Health Promot*. 2008; 22: 180-182.
7. Rhodes RE, Bruijn GJ. How big is the physical activity intention–behaviour gap? A meta-analysis using the action control framework. *Brit J Health Psych*. 2013; 18: 296-309.
8. Trost SG, Owen N, Bauman AE, Sallis JF, Brown W. Correlates of adults' participation in physical activity: review and update. *Med Sci Sport Exer*. 2002; 34: 1996-2001.
9. Baumeister RF, Vohs KD. Strength model of self-regulation as limited resource: Assessment, controversies, update. *Adv Exp Soc Psychol*. 2016; 54: 67-127.
10. Hagger MS, Wood CW, Stiff C, Chatzisarantis NL. Self-regulation and self-control in exercise: The strength-energy model. *Int Rev Sport Exer P*. 2010; 3: 62-86.
11. Inzlicht M, Schmeichel BJ. Beyond limited resources: Self-control failure as the product of shifting priorities. In Vohs K, Baumeister R, eds. The Handbook of Self-regulation: Research, Theory and Applications. 3rd ed. New York, NY: Guilford; 2016: 165-181.
12. Randall JG, Oswald FL, Beier ME. Mind-wandering, cognition, and performance: A theory-driven meta-analysis of attention regulation. *Psychol Bull*. 2014; 140: 1411-1431.
13. Hall PA. Executive-control processes in high-calorie food consumption. *Curr Dir Psychol Sci*. 2016; 25: 91-98.
14. Botvinick M, Braver T. Motivation and cognitive control: From behavior to neural mechanism. *Annu Rev Psychol*. 2015; 66: 83-113.

15. Hagger MS, Wood C, Stiff C, Chatzisarantis NL. Ego depletion and the strength model of self-control: a meta-analysis. *Psychol Bull*. 2010; 136: 495-525.
16. Friese M, Loschelder DD, Gieseler K, Frankenbach J, Inzlicht M. Is ego depletion real? An analysis of arguments *Pers Soc Psychol Rev*. 2018. Advance online publication. doi.org/10.1177/1088868318762183.
17. Boksem MA, Tops M. Mental fatigue: costs and benefits. *Brain Res Rev*. 2008; 59: 125-139.
18. Salmon J, Owen N, Crawford D, Bauman A, Sallis JF. Physical activity and sedentary behavior: a population-based study of barriers, enjoyment, and preference. *Health Psychol*. 2003; 22: 178-188.
19. Englert C, Wolff W. Ego depletion and persistent performance in a cycling task. *Int J Sports Psychol*. 2015; 6: 137-151.
20. Van Cutsem J, Marcora S, De Pauw K, Bailey S, Meeusen R, Roelands B. The effects of mental fatigue on physical performance: a systematic review. *Sports Med*. 2017; 47: 1-20.
21. Bray SR, Martin Ginis KA, Hicks AL, Woodgate J. Effects of self-regulatory strength depletion on muscular performance and EMG activation. *Psychophysiology*. 2008; 45: 337-343.
22. Graham JD, Martin Ginis KA, Bray SR. Exertion of self-control increases fatigue, reduces task self-efficacy, and impairs performance of resistance exercise. *Sport Exerc Perform Psychol*. 2017; 6: 70-88.
23. Marcora SM, Staiano W, Manning V. Mental fatigue impairs physical performance in humans. *J App Physiol*. 2009; 106: 857-864.
24. Zering JC, Brown DM, Graham JD, Bray SR. Cognitive control exertion leads to reductions in peak power output and VO2 Peak as well as increased perceived exertion on a graded exercise test to exhaustion. *J Sport Sci*. 2017; 35: 1799-1807.
25. Smith MR, Coutts AJ, Merlini M, Deprez D, Lenoir M, Marcora SM. Mental fatigue impairs soccer-specific physical and technical performance. *Med Sci Sport Exer*. 2016; 48: 267-276.
26. MacMahon C, Schücker L, Hagemann N, Strauss B. Cognitive fatigue effects on physical performance during running. *J Sport Exercise Psy*. 2014; 36: 375-381.
27. Schücker L, MacMahon C. Working on a cognitive task does not influence performance in a physical fitness test. *Psychol Sport Exerc*. 2016; 25: 1-8.
28. Martin Ginis KA, Bray SR. Application of the limited strength model of self-regulation to understanding exercise effort, planning and adherence. *Psychol Health*. 2010; 25: 1147-1160.
29. American College of Sports Medicine. ACSM's Guidelines for Exercise Testing and Prescription. Baltimore, MD: Wolters Kluwer; 2013.
30. Thomas S, Reading J, Shephard RJ. Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Can J Sport Sci*. 1992; 17: 338-345.

31. Faul F, Erdfelder E, Buchner A, Lang AG. Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. *Behav Res Methods*. 2009; 41:1149-1160.
32. McMorris T, Barwood M, Hale BJ, Dicks M, Corbett J. Cognitive fatigue effects on physical performance: A systematic review and meta-analysis. *Physiol Behav*. 2018; 188: 103-107. doi.org/10.1016/j.physbeh.2018.01.029
33. Booth ML, Ainsworth BE, Pratt M, et al. International physical activity questionnaire: 12-country reliability and validity. *Med Sci Sport Exer*. 2003; 195: 3508-1381.
34. Wewers ME, Lowe NK. A critical review of visual analogue scales in the measurement of clinical phenomena. *Res Nurs Health*. 1990; 13: 227-236.
35. Wood C, Magnello ME, Jewell T. Measuring vitality. Journal of the Royal society of Medicine. 1990; 83: 486-489.
36. Brown DMY, Bray SR. Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance. *Sport Exerc Perform Psychol*. 2017; 6: 355-369.
37. Borg G. Borg's Perceived Exertion and Pain Scales. Champaign, IL: Human Kinetics; 1998.
38. Barch DM, Braver TS, Nystrom LE, Forman SD, Noll DC, Cohen JD. Dissociating working memory from task difficulty in human prefrontal cortex. *Neuropsychologia*. 2009; 35: 1373-1380.
39. Pageaux B, Marcora S, Lepers R. Prolonged mental exertion does not alter neuromuscular function of the knee extensors. *Med Sci Sport Exer*. 2013; 45: 2254-2264.
40. Smith MR, Marcora SM, Coutts AJ. Mental fatigue impairs intermittent running performance. *Med Sci Sport Exer*. 2015; 47: 1682-1690.
41. Fothergill A, Attenborough D, Fenton G. *Planet Earth: Fresh Water* [DVD]. London, UK: BBC Video; 2007.
42. Morris SB, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychol Methods*. 2002; 7: 105-125.
43. American Psychological Association. Publication Manual of the American Psychological Association. 6th ed. Washington, DC: American Psychological Association; 2010.
44. Boksem MA, Meijman TF, Lorist MM. Effects of mental fatigue on attention: an ERP study. *Cognitive Brain Res.* 2005; 25: 107-116.
45. Boksem MA, Meijman TF, Lorist MM. Mental fatigue, motivation and action monitoring. *Biol Psychol.* 2006; 72: 123-132.
46. Chen MK. The epidemiology of self-perceived fatigue among adults. *Prev Med*. 1986; 15: 74-81.
47. Dittner AJ, Wessely SC, Brown RG. The assessment of fatigue: a practical guide for clinicians and researchers. *J Psychosom Res*. 2004; 56:157-170.

48. Pawlikowska T, Chalder T, Hirsch SR, Wallace P, Wright DJ, Wessely SC. Population based study of fatigue and psychological distress. *BMJ Brit Med J*. 1994; 308: 763-766.
49. Ricci JA, Chee E, Lorandeau AL, Berger J. Fatigue in the US workforce: prevalence and implications for lost productive work time. *J Occup Environ Med*. 2007; 49: 1-10.
50. Padula WV, Allen RR, Nair KV. Determining the cost of obesity and its common comorbidities from a commercial claims database. *Clin Obes*. 2014; 4: 53-58.
51. Tran BX, Nair AV, Kuhle S, Ohinmaa A, Veugelers PJ. Cost analyses of obesity in Canada: scope, quality, and implications. *Cost Eff Resour Alloc*. 2013; 11: 3.
52. Kemi OJ, Haram PM, Loennechen JP, Osnes JB, Skomedal T, Wisløff U, Ellingsen Ø. Moderate vs. high exercise intensity: differential effects on aerobic fitness, cardiomyocyte contractility, and endothelial function. *Cardiovasc Res*. 2005; 67: 161-172.
53. Swain DP, Franklin BA. Comparison of cardioprotective benefits of vigorous versus moderate intensity aerobic exercise. *Am J Cardiol*. 2006; 97: 141-147.
54. Kurzban R, Duckworth A, Kable JW, Myers J. An opportunity cost model of subjective effort and task performance. *Behav Brain Sci*. 2013; 36: 661-679.
55. Bray SR, Born HA. Transition to university and vigorous physical activity: implications for health and psychological well-being. *J Am Coll Health*. 2004; 52:181-188.
56. Kwan MY, Cairney J, Faulkner GE, Pullenayegum EE. Physical activity and other health-risk behaviors during the transition into early adulthood: a longitudinal cohort study. *Am J Prev Med*. 2012; 42: 14-20.
57. Rosenthal R. The effect of the experimenter on the results of psychological research. *Bulletin of the Maritime Psychological Association*. 1964; 13: 1–39.

Table 1. *Mental Fatigue during and following Cognitive Manipulations and Heart Rate during Cognitive Manipulations and Exercise by Condition.*

Measures	Low Cognitive Control *M* (*SD*)	High Cognitive Control *M* (*SD*)	*p* value	Effect size (Cohen's *d*)
Mental Fatigue AUC	167.76 (94.60)	242.04 (112.73)	.001*	.76
Mental Fatigue Final	42.12 (23.20)	59.84 (26.64)	.001*	.76
COG-HR_{AVE}	75.36 (7.87)	76.23 (7.79)	.45	.14
HR_{AVE}	159.05 (18.46)	151.55 (20.00)	.01*	.53

Note. * = significant main effect of Condition for 2x2 mixed ANOVA. AUC = area under the curve representing mental fatigue over 50-minutes of the cognitive control manipulations; COG-HR_{AVE} = average heart rate over 50-min cognitive manipulations; HR_{AVE} = average heart rate over 30 minutes of self-paced exercise.

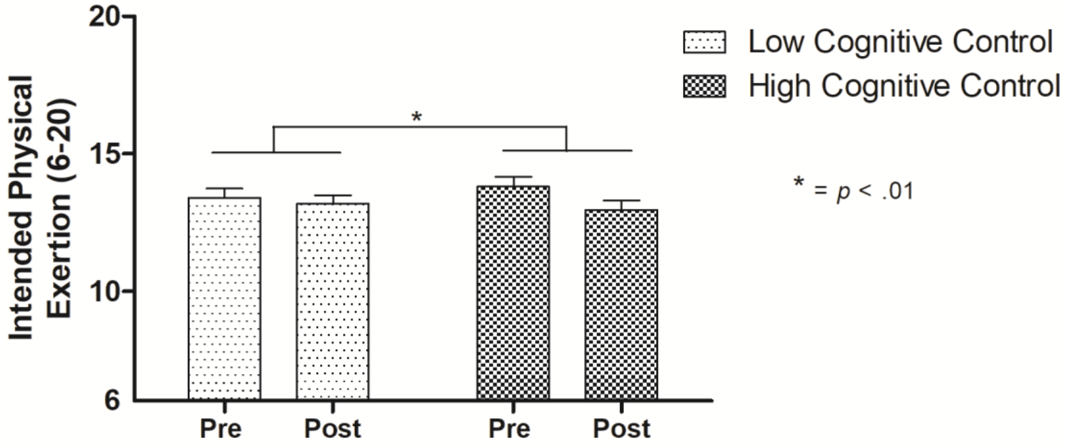


Figure 1. Intended physical exertion pre- and post-manipulation by condition. Bars represent standard error.

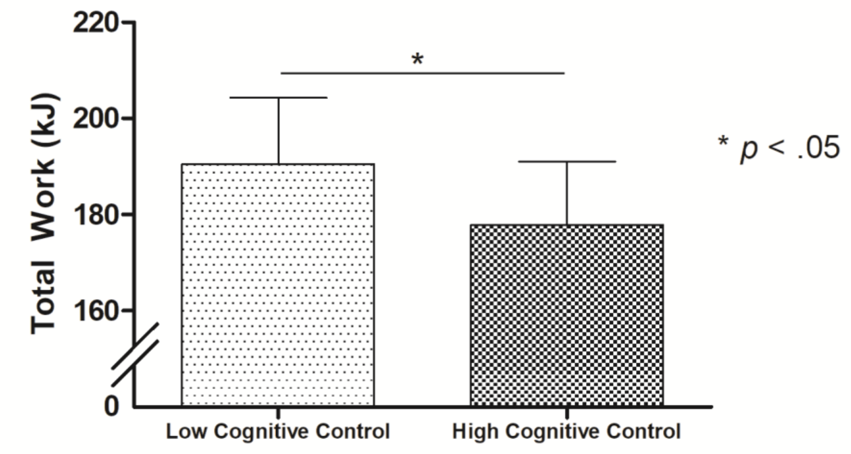


Figure 2. Total work (kJ) during the 30-min exercise sessions by condition. Bars represent standard error.

CHAPTER 5:

Heart rate biofeedback attenuates effects of mental fatigue on physical activity performance

Preamble

Heart rate biofeedback attenuates effects of mental fatigue on physical activity performance is the fourth study in the dissertation series. This study examined whether receiving heart rate biofeedback moderates the mental fatigue – physical performance relationship among a sample of insufficiently active university students performing public health guideline-based aerobic exercise. A secondary objective of this study was to examine whether predicted reductions for intended physical exertion and goal commitment correspond with expected exercise performance impairments.

The manuscript has been revised and resubmitted (under review currently) for publication in the journal *Psychology of Sport and Exercise* and has been formatted for this dissertation.

Contribution of Study 4 to overall dissertation

Study 4 builds on the findings of Study 3 by showing that receiving heart rate biofeedback moderates the effects of mental fatigue on vigorous-intensity exercise performance as per current intensity-based public health exercise prescription guidelines. Results also showed that mental fatigue was associated with decreases in intended physical exertion and commitment to vigorous-intensity exercise goals. Evidence suggests these motivational processes seem to translate into reductions in exercise intensity (i.e., HR_{AVE}) and total work performed in a fatigued state without feedback. Findings align with predictions of Control Theory and highlight that intervention strategies targeting self-regulatory factors are promising for coping with mental fatigue.

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: Repeated-measures, crossover design. Methods: Participants (*N* = 36) completed four 20-minute sessions of self-paced, cycling exercise. Exercise was preceded by 10-minute 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 monitoring 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 feedback, fatigued people may down-regulate exercise intensity.

Findings have implications for the use of behavioral-monitoring devices to improve intensity-based exercise prescription adherence when confronted with barriers such as mental fatigue.

Heart Rate Biofeedback Attenuates Effects of Mental Fatigue on Exercise Performance

For over a decade, public health agencies have endorsed physical activity (PA) guidelines that recommend adults engage in at least 150 minutes 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 & Deuchateau, 2016, pp. 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 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 refers to 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 = .44; 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 (Clarkson, Otto, Hassey & Hirt, 2016).

Although 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), a considerable body of evidence points to mental fatigue as a factor that impairs exercise performance (cf. Reviews by Englert, 2016 and Van Cutsem, Marcora, De Pauw, Bailey, Meeusen, & Roelands, 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-minute 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 (850m) 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 minutes 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 minutes 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.

Method

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 22.86 (*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* = .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 $\alpha = .01$, Inclusion criteria specified participants had intentions to meet, but were not currently meeting American College of Sports Medicine (ACSM; 2013) PA recommendations of ≥150 minutes of MVPA per week in the past 6 months, which was confirmed by self-reported weekly MVPA (*M* = 103.19 ± 30.19 minutes). 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 hours 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.

Measures

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).

Exercise Protocols

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-minute exercise training sessions. The GXT consisted of a 3-minute warm-up at 50 Watts (W) resistance at >50 RPM, after which resistance was automatically increased by 1 W / 2 seconds 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.

Self-paced exercise training sessions. Participants completed six, 20-minute, self-paced bouts of exercise on a cycle ergometer at a self-determined cadence >50 RPM. Sessions began with a 3-minute warm-up at 50W 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 (α = .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-minute exercise session, the ergometer was re-set to a workload of 50W and participants performed a 3-minute 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.

Cognitive Control Experimental Manipulations

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

High cognitive control (HCC)task. Participants performed a computerized version of the incongruent color-word Stroop task (Stroop, 1935) using Presentation^{TM} 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-minute 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 “red”, they would say aloud the word “red”).

Low cognitive control (LCC) task. Participants watched five, 2-minute segments of a documentary film (*Planet Earth: Fresh Water*; Fothergill, Attenborough & Fenton, 2007) on a 17” computer monitor. To ensure attention was engaged throughout the duration of the task, participants were asked to monitor the audio commentary and recorded instances when they heard a key word: "*water*". Similar manipulations have been used as low cognitive control tasks in numerous investigations (e.g., Brown & Bray, 2017a, 2017b; Marcora et al., 2009).

Biofeedback Manipulations

To conform to overarching efforts to use common language across literatures, we have operationalized the manipulation of providing HR feedback while exercising as “Biofeedback” as per Michie et al.’s (2015, p. 121) 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.

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.

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

Psychological Variables

Mental demand. Participants rated how mentally demanding each of the cognitive control manipulations was using the Mental Demand subscale 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*).

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-minute period, the five mental fatigue scores were summed to calculate the AUC.

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 $\alpha \geq .84$).

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.

Intended physical exertion (Intended RPE). Participants rated their intended RPE for each 20-minute 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.

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 14-17 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 $\alpha \geq .80$).

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-minute intervals during each of the 20-minute exercise sessions and scores were averaged to compute the variable: RPE_{AVE} for each session.

Physiological Variables

HR. HR was recorded continuously throughout each of the GXTs, 20-minute exercise training sessions, and the 10-minute 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-minute 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-minute experimental manipulation window.

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

Procedure

Participants attended eight laboratory sessions. 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 x 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 minutes 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-minute 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-minute 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 hours 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).

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-HR$_{\text{AVE,}}$ 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.

Results

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 = .84, M_{Change} = -8.03 ± 10.28). Declines in performance on the HCC task provide a secondary, objective, indicator of increased mental fatigue (e.g., Boksem, Meijman & Lorist, 2005).

Intrinsic motivation. Analyses of intrinsic motivation values (Table 1) showed no differences between the Cognitive Control conditions, F (1, 35) = .07, p = .80, η_p^2 = .00.

Task motivation. Analyses of task motivation values (Table 1) show no significant difference between the Cognitive Control conditions, F (1, 35) = 3.54, p = .07, η_p^2 = .09.

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, η_p^2 = .97.

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, η_p^2 = .66 (Table 1).

COG-HR$_{\text{AVE}}$. Results showed significantly greater average HR during the HCC task compared to the LCC task, *F* (1, 35) = 32.73, $p < .001$, $\eta_p^2 = .48$ (Table 1).

Main Analyses

Effects of Cognitive Control Experimental Manipulations on Pre-Exercise Psychological Variables

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, $\eta_p^2 = .03$, and Time, *F* (1, 35) = 1.40, *p* = .25, $\eta_p^2 = .04$, but a significant interaction, *F* (1, 35) = 7.24, *p* = .01, $\eta_p^2 = .17$. Decomposing the interaction using paired *t*-tests of the pooled means for the HCC and LCC conditions with a Bonferroni correction (adjusted $\alpha = .025$) revealed a significant decrease in intended RPE scores in the HCC conditions, *t* (71) = 2.50, *p* = .02, *d* = -.30, but no change in the LCC conditions, *t* (71) = -1.58, *p* = .12, *d* = .18.

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, $\eta_p^2 = .13$, Time, *F* (1, 35) = 12.89, *p* = .001, $\eta_p^2 = .27$, and Cognitive Control X Time interaction, *F* (1, 35) = 17.09, *p* <.001, $\eta_p^2 = .33$. Decomposing the interaction using paired *t*-tests with a Bonferroni correction (adjusted $\alpha = .025$) of the pooled means for the HCC and LCC conditions showed a significant decrease in goal commitment in the HCC conditions, $t\ (71) = 4.78$, $p < .001$, $d = -.59$, but no change in the LCC conditions, $t\ (71) = .38$, $p = .71$, $d = .04$.

Effects of Experimental Manipulations on Heart Rate, Behavior, and RPE during Exercise

PEAKHR%$_{\text{AVE}}$. Values for PEAKHR%$_{\text{AVE}}$ for the exercise sessions are presented by condition, in Figure 1. Results revealed significant main effects for Cognitive Control, $F\ (1, 35) = 12.22$, $p = .001$, $\eta_p^2 = .26$, Biofeedback, $F\ (1, 35) = 20.70$, $p < .001$, $\eta_p^2 = .37$, and a Cognitive Control X Biofeedback interaction, $F\ (1, 35) = 15.24$, $p < .001$, $\eta_p^2 = .30$. Post-hoc planned contrasts (Bonferroni) were computed between each condition to decompose the interaction, which showed participants exercised at virtually-identical heart rates (*p*s = 1.0) 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 (*p*s < .001).

Total work. Accumulated energy (kJ) for each of the exercise sessions is displayed, by condition, in Figure 1. Results revealed significant main effects for Cognitive Control, $F\ (1, 35) = 11.21$ $p = .002$, $\eta_p^2 = .24$, Biofeedback, $F\ (1, 35) = 9.96$, $p = .003$, $\eta_p^2 = .22$, and a significant interaction, $F\ (1, 35) = 5.23$, $p = .028$, $\eta_p^2 = .13$. 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 (*p*s $\leq .002$) 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 (all *p*s = 1.0).

RPE_{AVE}. RPE_{AVE} values for the four conditions were as follows: LCC/no feedback (*M* = 14.53 ± 1.09), LCC/biofeedback (*M* = 14.70 ± 1.32), HCC/no feedback (*M* = 14.42 ± 1.28), and HCC/biofeedback (*M* = 14.99 ± 1.75). Analyses showed a significant main effect of Biofeedback, *F* (1, 35) = 5.40, *p* = .03, η_p^2 = .13), with greater RPE in the biofeedback conditions. The main effect for Cognitive Control, *F* (1, 35) = .43, *p* = .52, η_p^2 = .01, and the Cognitive Control X Biofeedback interaction were not significant, *F* (1, 35) = 2.01, *p* = .17, η_p^2 = .05.

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 no-monitoring 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-minute 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 20km 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 these 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 mentally fatiguing and non-fatiguing 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 $\text{PEAKHR\%}_{\text{AVE}}$) 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, Rao, Lai, Abernethy, Rosenbloom & Cella, 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-minute 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.

References

American College Health Association (2015). *American College Health Association - national college health assessment II: Undergraduate students reference group data report spring 2015*. Hanover, MD: American College Health Association.

American College of Sports Medicine. (2013). *ACSM's guidelines for exercise testing and prescription*. Baltimore, MD: Wolters Kluwer.

Aritake, S., Kaneita, Y., Ohtsu, T., Uchiyama, M., Mishima, K., Akashiba, T., ... & Ohida, T. (2015). Prevalence of fatigue symptoms and correlations in the general adult population. *Sleep and Biological Rhythms, 13*, 146-154. doi:10.1111/sbr.12099

Baumeister, R. F., & Vohs, K. D. (2016). Strength model of self-regulation as limited resource: Assessment, controversies, update. *Advances in Experimental Social Psychology, 54,* 67-127. doi:10.1016/bs.aesp.2016.04.001

Boksem, M. A., Meijman, T. F., & Lorist, M. M. (2005). Effects of mental fatigue on attention: an ERP study. *Cognitive Brain Research, 25*, 107-116. doi:10.1016/j.cogbrainres.2005.04.011

Boksem, M. A., & Tops, M. (2008). Mental fatigue: costs and benefits. *Brain Research Reviews*, *59*, 125-139. doi:10.1016/j.brainresrev.2008.07.001

Borg, G. (1998). *Borg's perceived exertion and pain scales*. Champaign, IL: Human Kinetics.

Borg, G., Hassmén, P., & Lagerström, M. (1987). Perceived exertion related to heart rate and blood lactate during arm and leg exercise. *European Journal of Applied Physiology and Occupational Physiology, 56*, 679-685. doi:10.1007/BF00424810

Brown, D. M. Y., & Bray, S. R. (2018). Effects of mental fatigue on exercise intentions and behavior. *Annals of Behavioral Medicine*. Advance online publication. doi:10.1093/abm/kay052

Brown, D. M. Y., & Bray, S. R. (2017a). Graded increases in cognitive control exertion reveal a threshold effect on subsequent physical performance. *Sport, Exercise, and Performance Psychology, 6*, 355-369. doi:10.1037/spy0000091

Brown, D. M. Y., & Bray, S. R. (2017b). Effects of mental fatigue on physical endurance performance and muscle activation are attenuated by monetary incentives. *Journal of Sport and Exercise Psychology, 39*, 385-396. doi:10.1123/jsep.2017-0187

Butt, Z., Rao, A. V., Lai, J. S., Abernethy, A. P., Rosenbloom, S. K., & Cella, D. (2010). Age-associated differences in fatigue among patients with cancer. *Journal of Pain and Symptom Management, 40*, 217-223. doi:10.1016/j.jpainsymman.2009.12.016

Carver, C. S., & Scheier, M. F. (1982). Control theory: A useful conceptual framework for personality–social, clinical, and health psychology. *Psychological Bulletin, 92*, 111-135. doi:10.1037/0033-2909.92.1.111

Clarke, T. C., Norris, T., & Schiller, J. S. (2017). *Early release of selected estimates based on data from 2016 National Health Interview Survey*. National Center for Health Statistics.

Clarkson, J. J., Otto, A. S., Hassey, R., & Hirt, E. R. (2016). Perceived mental fatigue and self-control. In E. R. Hirt, J. J. Clarkson & L. Jia, (Eds.), *Self-Regulation and Ego Control* (pp. 185-202). Cambridge, MA: Academic Press. doi:10.1016/B978-0-12-801850-7.00010-X

Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., ... & Oja, P. (2003). International Physical Activity Questionnaire: 12-country reliability and validity. *Medicine & Science in Sports & Exercise, 35*, 1381-1395. doi:10.1249/01.mss.0000078924.61453.fb

De Ridder, D. T., Lensvelt-Mulders, G., Finkenauer, C., Stok, F. M., & Baumeister, R. F. (2012). Taking stock of self-control: A meta-analysis of how trait self-control relates to a wide range of behaviors. *Personality and Social Psychology Review,16*,76-99.doi:10.1177/1088868311418749

Englert, C. (2016). The strength model of self-control in sport and exercise psychology. *Frontiers in Psychology, 7,* 314. doi:10.3389/fpsyg.2016.00314

Englert, C., & Rummel, J. (2016). I want to keep on exercising but I don't: The negative impact of momentary lacks of self-control on exercise adherence. *Psychology of Sport and Exercise*, *26*, 24-31. doi:10.1016/j.psychsport.2016.06.001

Enoka, R. M., & Duchateau, J. (2016). Translating fatigue to human performance. *Medicine & Science in Sports & Exercise*, *48*, 2228-2238. doi:10.1249/mss.0000000000000929

Fothergill, A., Attenborough, D., & Fenton, G. (2007). *Planet earth: Fresh water*. BBC Video.

Godin, G., & Conner, M. (2008). Intention-behavior relationship based on epidemiologic indices: an application to physical activity. *American Journal of Health Promotion*, *22*, 180-182. doi:10.4278/ajhp.22.3.180

Hagger, M. S., Wood, C., Stiff, C., & Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: a meta-analysis. *Psychological Bulletin*, *136*, 495-525. doi:10.1037/a0019486

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology*, *52*, 139-183. doi:10.1016/S0166-4115(08)62386-9

Haskell, W. L., Lee, I. M., Pate, R. R., Powell, K. E., Blair, S. N., Franklin, B. A., ... & Bauman, A. (2007). Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Circulation, 116*, 1081-1093. doi:10.1161/circulationaha.107.185649

Hockey, R. (2013). *The psychology of fatigue: Work, effort and control*. New York, NY: Cambridge University Press. doi:10.1017/CBO9781139015394

Inzlicht, M., Bartholow, B. D., & Hirsh, J. B. (2015). Emotional foundations of cognitive control. *Trends in Cognitive Sciences, 19,* 126-132. doi:10.1016/j.tics.2015.01.004

Inzlicht, M., & Schmeichel, B. J. (2012). What is ego depletion? Toward a mechanistic revision of the resource model of self-control. *Perspectives on Psychological Science*, *7*, 450-463. doi:10.1177/1745691612454134

Khaodhiar, L., McCowen, K. C., & Blackburn, G. L. (1999). Obesity and its comorbid conditions. *Clinical Cornerstone, 2*, 17-31. doi:10.1016/S1098-3597(99)90002-9

Klein, H. J., Wesson, M. J., Hollenbeck, J. R., & Alge, B. J. (1999). Goal commitment and the goal-setting process: conceptual clarification and empirical synthesis. *Journal of Applied Psychology, 84*, 885-896. doi:10.1037//0021-9010.84.6.885

Klein, H. J., Wesson, M. J., Hollenbeck, J. R., Wright, P. M., & DeShon, R. P. (2001). The assessment of goal commitment: A measurement model meta-analysis. *Organizational Behavior and Human Decision Processes, 85*, 32-55. doi:10.1006/obhd.2000.2931

Locke, E. A., Latham, G. P., & Erez, M. (1988). The determinants of goal commitment. *Academy of Management Review, 13*, 23-39. doi:10.5465/amr.1988.4306771

Luethi, M. S., Friese, M., Binder, J., Boesiger, P., Luechinger, R., & Rasch, B. (2016). Motivational incentives lead to a strong increase in lateral prefrontal activity after self-control exertion. *Social Cognitive and Affective Neuroscience, 11*, 1618-1626. doi:10.1093/scan/nsw073

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive fatigue effects on physical performance during running. *Journal of Sport and Exercise Psychology*, *36*, 375-381. doi:10.1123/jsep.2013-0249

Macridis, S., Johnston, N., Johnson, S., & Vallance, J. K. (2018). Consumer physical activity tracking device ownership and use among a population-based sample of adults. *PloS one*, *13*, e0189298. doi:10.1371/journal.pone.0189298

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology, 106*, 857-864. doi:10.1152/japplphysiol.91324.2008

Martin, S. B., Morrow Jr, J. R., Jackson, A. W., & Dunn, A. L. (2000). Variables related to meeting the CDC/ACSM physical activity guidelines. *Medicine & Science in Sports & Exercise*, *32*, 2087-2092. doi:10.1097/00005768-200012000-00019

Martin Ginis, K. A., & Bray, S. R. (2010). Application of the limited strength model of self-regulation to understanding exercise effort, planning and adherence. *Psychology and Health*, *25*, 1147-1160. doi:10.1080/08870440903111696

McMorris, T., Barwood, M., Hale, B. J., Dicks, M., & Corbett, J. (2018). Cognitive fatigue effects on physical performance: A systematic review and meta-analysis. *Physiology & Behavior*. *188*, 103-107. doi:10.1016/j.physbeh.2018.01.029

Michie, S., & Johnston, M. (2012). Theories and techniques of behaviour change: Developing a cumulative science of behaviour change. *Health Psychology Review*, *6*, 1-6, doi:10.1080/17437199.2012.654964

Michie, S., Wood, C. E., Johnston, M., Abraham, C., Francis, J., & Hardeman, W. (2015). Behaviour change techniques: the development and evaluation of a taxonomic method for reporting and describing behaviour change interventions (a suite of five studies involving consensus methods, randomised controlled trials and analysis of qualitative data). *Health Technology Assessment*, *19*, 1-187. doi:10.3310/hta19990

Morris, S. B., & DeShon, R. P. (2002). Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. *Psychological methods*, *7*(1), 105-125. doi:10.1037//1082-989x.7.1.105

Müller, T. & Apps, M. A. (In Press). Motivational fatigue: A neurocognitive framework for the impact of effortful exertion on subsequent motivation. *Neuropsychologia*. doi:10.1016/j.neuropsychologia.2018.04.030

Nicolò, A., Marcora, S. M., & Sacchetti, M. (2016). Respiratory frequency is strongly associated with perceived exertion during time trials of different duration. *Journal of Sports Sciences*, *34*, 1199-1206. doi:10.1080/02640414.2015.1102315

Pageaux, B., Lepers, R., Dietz, K. C., & Marcora, S. M. (2014). Response inhibition impairs subsequent self-paced endurance performance. *European Journal of Applied Physiology*, *114*, 1095-1105. doi:10.1007/s00421-014-2838-5

Parfitt, G., Rose, E. A., & Burgess, W. M. (2006). The psychological and physiological responses of sedentary individuals to prescribed and preferred intensity exercise. *British Journal of Health Psychology*, *11*, 39-53. doi:10.1348/135910705x43606

Pires, F. O., Silva-Júnior, F. L., Brietzke, C., Franco-Alvarenga, P. E., Pinheiro, F. A., de França, N. M., ... & Meireles Santos, T. (2018). Mental fatigue alters cortical activation and psychological responses, impairing performance in a distance-based cycling rrial. *Frontiers in Physiology*, *9*, 227. doi:10.3389/fphys.2018.00227

Rebar, A. L., Dimmock, J. A., Rhodes, R. E., & Jackson, B. (2018). A daily diary approach to investigate the effect of ego depletion on intentions and next day behavior. *Psychology of Sport and Exercise*, *39*, 38-44. doi:10.1016/j.psychsport.2018.07.010

Ricci, J. A., Chee, E., Lorandeau, A. L., & Berger, J. (2007). Fatigue in the US workforce: prevalence and implications for lost productive work time. *Journal of Occupational and Environmental Medicine*, *49*, 1-10. doi:10.1097/01.jom.0000249782.60321.2a

Ryan, R. M. (1982). Control and information in the intrapersonal sphere: An extension of cognitive evaluation theory. *Journal of Personality and Social Psychology, 43*, 450-461. doi:10.1037/0022-3514.43.3.450

Salmon, J., Owen, N., Crawford, D., Bauman, A., & Sallis, J. F. (2003). Physical activity and sedentary behavior: a population-based study of barriers, enjoyment, and preference. *Health Psychology*, *22*, 178-188. doi:10.1037//0278-6133.22.2.178

Public Health Agency of Canada (2016). *Health status of Canadians 2016*. Government of Canada.

Schöndube, A., Bertrams, A., Sudeck, G., & Fuchs, R. (2017). Self-control strength and physical exercise: an ecological momentary assessment study. *Psychology of sport and exercise*, *29*, 19-26. doi:10.1016/j.psychsport.2016.11.006

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643-662. doi:10.1037/h0054651

Swain, D. P., & Franklin, B. A. (2006). Comparison of cardioprotective benefits of vigorous versus moderate intensity aerobic exercise. *American Journal of Cardiology*, *97*, 141-147. doi:10.1016/j.amjcard.2005.07.130

Thomas, S., Reading, J., & Shephard, R. J. (1992). Revision of the physical activity readiness questionnaire (PAR-Q). *Canadian Journal of Sport Sciences. 17*, 338-345.

Van Cutsem, J., Marcora, S., De Pauw, K., Bailey, S., Meeusen, R., & Roelands, B. (2017). The effects of mental fatigue on physical performance: a systematic review. *Sports Medicine, 47*, 1569-1588. doi:10.1007/s40279-016-0672-0

Voce, A. C., & Moston, S. (2016). Does Monitoring Performance Eliminate the Ego-depletion Phenomenon and Influence Perception of Time?. *Self and Identity*, *15*, 32-46. doi:10.1080/15298868.2015.1074101

Wan, E. W., & Sternthal, B. (2008). Regulating the effects of depletion through monitoring. *Personality and Social Psychology Bulletin*, *34*, 32-46. doi:10.1177/0146167207306756

Wewers, M. E., & Lowe, N. K. (1990). A critical review of visual analogue scales in the measurement of clinical phenomena. *Research in Nursing & Health,13*, 227-236.doi:10.1002/nur.4770130405

Williams, E. J. (1949). Experimental designs balanced for the estimation of residual effects of treatments. *Australian Journal of Chemistry*, *2*, 149-168. doi.org/10.1071/ch9490149

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-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-minutes of the cognitive control manipulations; COG-HR$_{AVE}$ = average heart rate over 10 minutes of the cognitive task experimental manipulation; Pre = pre-cognitive task; Post = post-cognitive task.

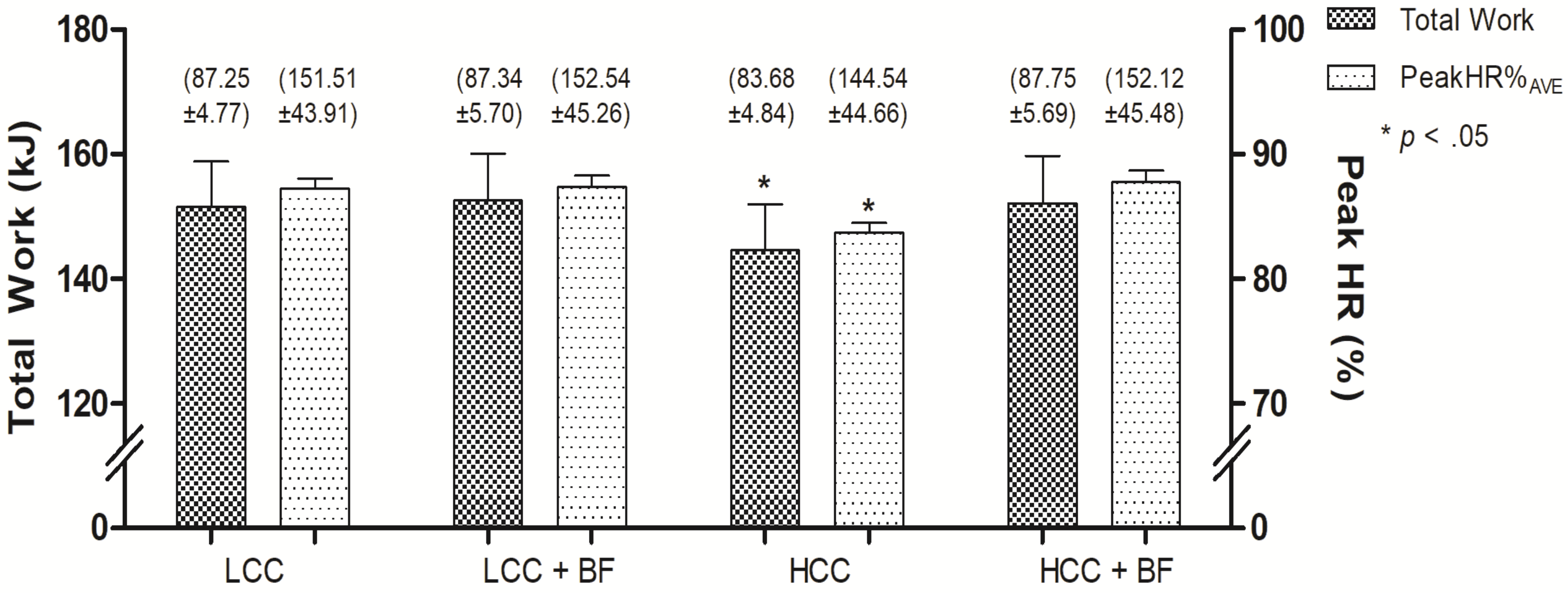


Figure 1. Average Percentage of Peak Heart Rate and Total Work performed during exercise by Condition. Bars represent standard error. Numerical text above bars represent *M* ± *SD*. * indicates values for Total Work and HR Peak (%) for HCC differ significantly ($p < .05$) from the other conditions. All other condition-condition values are not significantly different ($p > .05$).

CHAPTER 6:

GENERAL DISCUSSION

The negative effects of mental fatigue and self-control exertion on physical performance have been documented in the literature for over a decade, yet our understanding of psychological and physiological factors that underlie these effects is not well-developed. The overarching objective of this dissertation was to investigate the association between mental fatigue and physical activity behaviour and systematically examine potential mediators and moderators of the mental fatigue - physical performance relationship.

Overall, the findings have extended existing knowledge in several important areas. To summarize: the main findings show that brief doses of cognitive control exertion do not affect physical performance; however, uniform physical performance impairments occur beyond a critical mental fatigue threshold (Study 1). Mental fatigue corresponded with reductions among several psychological variables including affective valence (Study 1), task self-efficacy (Study 1), intended physical exertion (Studies 3 & 4) and goal commitment (Study 4) which seem to translate into subsequent decreases for physical performance (Studies 1, 3 & 4). Offering performance contingent incentives (Study 2) and enabling people to monitor their behaviour using objective biofeedback (Study 4) showed promising effects for counteracting fatigue-induced performance impairments to levels achieved in a non-fatigued state. Findings also provide evidence that the deleterious effects of mental fatigue are generalizable to the broader population performing guideline based aerobic exercise for health and fitness benefits (Studies 3 & 4). The following sections will highlight the theoretical and practical implications of this work, address its shortcomings, and consider future directions for inquiry in this area.

Conceptual Implications

The studies undertaken for this dissertation were designed to test a variety of theoretical premises that have been advanced in the area of self-regulation. The findings lend support to existing theories in several ways and point to new questions that contribute to our conceptual understanding of the relationship between mental fatigue and physical performance by identifying potential mediators and moderators of this relationship. Previous research examining the relationship between ego depletion or mental fatigue and physical performance had not tested whether a dose-response relationship exists. Study 1 addressed this limitation, providing the first evidence that incrementally increasing grades of effortful cognitive control exertion did not lead to further decreases in performance despite linear increases in mental fatigue. Instead, findings showed uniform negative effects for physical performance beyond a threshold (i.e., between 4 to 6 mins). These findings align with those of a previous study showing a within-domain (i.e., cognitive to cognitive) threshold effect following exposure to increasing grades of a cognitive self-control task (vanDellen, Hoyle & Miller, 2012). Given the brevity of the manipulations which elicited a threshold effect (i.e., ≤ 10 minutes), future research should examine larger grades of increasing effortful cognitive exertion (i.e., > 10 minutes) to determine whether performance impairments remain uniform at the same threshold or whether the shape of the relationship changes at greater doses.

Beyond establishing a threshold effect for mental fatigue and physical performance, findings from Study 1 also identified a number of potential mechanistic processes underlying this relationship. Results showed that mental fatigue, self-efficacy, and affective valence were all correlated with physical performance, however, task self-efficacy was the only significant mediating variable. This finding supports Bandura's (1997) theorizing regarding the influential role of self-efficacy for self-regulation and extends previous work of Graham and Bray (2015) by showing reductions in task self-efficacy may also elicit a threshold effect. Although task self-efficacy is not explicitly represented within recent motivational accounts of self-control processes (e.g., Process/shifting priorities model; Inzlicht & Schmeichel, 2012, 2016; Inzlicht et al., 2014), self-efficacy is a motivational cognition that, in concert with outcome expectations, determines how people behave (Bandura, 1997) and could therefore be considered a specific characteristic of motivation that provides some support for this line of theorizing.

Study 2 also provided support for motivational accounts of self-control; showing evidence that incentives moderate the effect of mental fatigue on physical performance. Specifically, when fatigued people were offered a small monetary reward for matching or exceeding their prior performance, they were able to do so; while this was not the case when a reward was not offered.

However, it is interesting to note that incentives offered no additional benefit to participants in a non-fatigued state. These results are similar to those reported in other studies examining the effects of incentives on self-control (Luethi et al., 2016; Muraven & Slessareva, 2003). The consistency in these findings is remarkable, suggesting that people may be hypersensitive to rewards or the subjective value of a reward may be greater when they are in a mentally-fatigued state.

Although the purpose of this dissertation is to examine the mental fatigue – physical performance relationship from a psychological perspective, data related to physiological adaptations (electromyography) highlight the central role of the brain in motivated behaviour. That is, Study 2 demonstrated first evidence that reward stimuli may stimulate restorative processes that allow normal activation of neuromuscular circuits and counteract fatigue-induced performance impairments to levels witnessed in a non-fatigued state. These results can be interpreted within Müller and Apps (2018) neurocognitive framework of motivational fatigue as the increased dopaminergic activity associated with a reward stimulus may have altered the potential energetic cost of sustained effortful physical exertion, making it more worthwhile when behaviour was incentivized. Future research should investigate the subjective value of incentives other than money on the performance of physical activity when mentally fatigued as well as the extent to which the amount of perceived effort involved in a physical task may lead people to discount the value of performance-contingent rewards.

Study 3 was distinct from Studies 1 and 2 insofar as participants were able to control how they performed the physical task rather than the amount of time the task was performed for. In doing so, results showed mental fatigue lead to down-regulation of exercise performance in terms of total work performed and the intensity at which exercise was performed (i.e., average heart rate). These findings can be interpreted in light of motivational accounts of self-control as fatigue may have increased the cost of exercising by making it feel more effortful, leading participants to draw back their effort in favour of a more leisurely pace. However, the results may also support the resource perspective as a reduction in resources may have prompted less motivation to expend additional resources (Baumeister & Vohs, 2016). Overall, the results of Study 3 offer evidence that when people decide to be physically active, engaging in guideline-based exercise for health and fitness benefits, fatigue-induced effects may alter their decision-making processes related to effortful exertion.

Another interesting finding from Study 3 is that mental fatigue altered the effort people intended to exert before they even began exercising. These results support previous findings by Martin Ginis and Bray (2010), which also showed people's intended physical exertion was affected by prior cognitive exertion and extend the literature by showing that reductions in effort-based intentions correspond with reductions in exercise performance. These findings also serve to illustrate that effort-based intentions are another proximal indicator of motivation not explicitly identified in motivational accounts of self-control. Changes in this construct may reflect alterations in one’s cost-benefit valuation processes (Milyavskaya & Inzlicht, 2017), which would be consistent with motivational lines of theorizing, but leave open the question as to whether shifts in motivation result from internal signals that energetic resources have been depleted (cf., Ampel, Muraven & McNay, 2018).

Study 4 built on the findings of Study 3 by examining the moderating role of heart rate biofeedback on self-regulation of physical activity behaviour when mentally fatigued. This study was conceptually distinct from previous studies as it examined this research question from the perspective of control theory (Carver & Scheier, 1982). Consistent with predictions of control theory, exposure to a perturbation (i.e., mental fatigue) impaired regulation of exercise behaviour, resulting in a 5% reduction in total work and average heart rate while exercising. However, having a goal and externally-monitoring behaviour using heart rate biofeedback effectively negated fatigue-induced performance reductions to levels witnessed in a non-fatigued state. It is worthwhile to note that biofeedback offered no benefits for performance when people were in a non-fatigued state and provide additional evidence that interventions (e.g., the rewards offered in Study 2) may work through motivational mechanisms that have heightened responsiveness when delivered to people who are fatigued. Overall, findings provide initial evidence that intervention strategies targeting self-regulatory factors can moderate the effect of mental fatigue on physical performance and may have important applications for adherence to public health exercise guidelines.

Study 4 also contributed to motivational accounts of self-control by showing further evidence of reductions in self-reported measures indicative of precise motivational processes following effortful cognitive exertion. Specifically, findings are the first to show people’s commitment to exercise goals is decreased due to mental fatigue, which directly corresponded with downward changes in their intended physical exertion. Although changes for goal commitment and intended physical exertion appear to translate into deceases in exercise performance, further research is needed to test whether these precise motivational processes are a causal mechanism determining changes in behaviour. Examining sequential mediation models testing potential pathways such as effortful cognitive exertion → mental fatigue → goal commitment/intended RPE → physical performance have the potential to shed light on the complex role motivational processes underlying the mental fatigue – physical performance relationship.

Müller and Apps (2018) recently presented a neurocognitive framework of motivational fatigue. Although this perspective is not specific to physical activity behaviour, the authors provide a mechanistic process, which helps to explain the findings witnessed across the four studies within this dissertation. Neuroimaging research has consistently shown that effortful cognitive exertion causes alterations in activation patterns among brain regions (i.e., dorsolateral prefrontal cortex, dorsal anterior cingulate cortex and anterior insula) that have been shown to be crucial for monitoring fatigue and motivation to exert effort. Müller and Apps argue that as these regions detect internal perturbations to homeostatic equilibrium and that sensations of fatigue, generated in these areas, are signals that exerting effort is less worthwhile, resulting in premature task withdrawal (Studies 1 & 2), or down-regulation of effort (Studies 3 & 4). Research within the area of mental fatigue and physical performance has recently begun to examine how alterations in these key brain regions affect physical performance and psychological perceptions and cognitions during exercise. Evidence suggests effortful cognitive exertion causes hyperactivation within the prefrontal cortex which persists while exercising, resulting in a 2.7% performance reduction as well as exacerbated perceptions of exertion and lower ratings of task motivation (Pires et al., 2018). These findings implicate the prefrontal cortex in the top-down regulation of effort during exercise and provide evidence that brain regions underlying motivation-based decision making processes that drive goal-directed behaviour are affected by mental fatigue.

Müller and Apps (2018) also contend that internal and extrinsic motivational "boosts" can overcome the elevated costs of additional effortful exertion caused by fatigue by creating a motivational structure that increases the salience of goals/standards and reinforces a pathway towards goal pursuit. Luethi et al. (2016) have shown effortful cognitive exertion causes maladaptive neural activation patterns within prefrontal brain regions, which are associated with subsequent cognitive self-control impairments. However, offering incentives serves to recalibrate prefrontal activation patterns to normal, which then correspond with normal performance on tasks requiring cognitive control. As explained in Study 2, the effects of incentives on muscle activation patterns and physical performance share key similarities with Leuthi et al.'s findings. Evidently, rewards or motivation are influential factors that facilitate neurological adaptations in the face of fatigue. Given the similarity between the moderating effects of incentives and heart rate biofeedback on physical performance (Studies 2 & 4), Luethi et al.'s findings support the notion that a common set of neurological processes that govern effort regulation are responsible for changes in performance when fatigued and how these effects dissipate in response to reward-based intervention strategies.

Collectively, the studies within this dissertation identified moderators and potential mediating factors of the mental fatigue - physical performance relationship. Findings provide support for resource based (Baumeister & Vohs, 2016) and motivational accounts of self-control (Inzlicht & Schmeichel, 2012, 2016; Inzlicht et al., 2014; Kotabe & Hofmann, 2015; Kurzban et al., 2013) as well as control theory (Carver & Scheier, 1982), while also demonstrating results consistent with theorizing by Bandura (1997) regarding the potent role of self-efficacy for physical performance. Müller and Apps (2018) neurocognitive framework of motivational fatigue provides insight regarding neurological mechanisms that explain why effortful cognitive exertion results in subsequent behavioural impairments, and also how incentives and heart rate biofeedback can effectively counteract fatigue-induced effects. As a result, findings from the current studies have several practical applications and implications for understanding and improving self-regulation of physical activity behaviour when faced with barriers such as mental fatigue.

Practical Implications

Alongside the conceptual contributions outlined in the previous section, the findings of this dissertation highlight a number of practical implications for understanding the influence of mental fatigue on self-regulation of physical activity behaviour and countering these effects in "real world" situations outside the laboratory. First, results from Study 1 suggest that exercisers and athletes should be conscious about effortful cognitive exertion preceding exercise, training or competition. Identifying situations potentially involving high cognitive demands that could accumulate and exceed a critical fatigue threshold may be crucial for avoiding sub-optimal performances. People should also be cognizant that fatigue may naturally increase throughout the course of the day (Micklewright, St. Clair Gibson, Gladwell & Al Salman, 2017) and, as a result, it may take less effortful cognitive exertion to surpass the threshold later in the day compared to earlier on. Therefore, scheduling one's activities to avoid having to exert physical effort shortly after performing other effortful tasks or incorporating a period of rest/recovery prior to exercising may be practical strategies to help avoid fatigue-induced performance impairments.

Studies 3 and 4 showed that mental fatigue not only affects active people and trained athletes performing highly demanding physical exercises (e.g., MacMahon, Schücker, Hagemann & Strauss, 2009; Marcora, Staiano & Manning, 2009), but also extends to insufficiently active people engaging in exercise behaviour reflective of current public health recommendations for health and fitness benefits. These findings have implications for the majority of the North American population, given that 8 out of every 10 people do not accrue the recommended 150 minutes of weekly moderate-to-vigorous physical activity (MVPA) (Clarke, Norris & Schiller, 2017; Public Health Agency of Canada, 2016). As widespread health promotion efforts attempt to improve physical activity participation levels among the general population, practitioners promoting physical activity and people endeavouring to adopt more active lifestyles should be aware that mental fatigue is not only a common barrier to initiating physical activity behaviour (Salmon, Owen, Crawford, Bauman & Sallis, 2002), but also a performance-limiting factor during exercise.

Experiencing mental fatigue-induced reductions in aerobic exercise performance (Studies 3 & 4) has important implications as it could potentially curb health benefits associated with meeting recommended exercise intensities. For example, cardiovascular adaptations to exercise are intensity dependent (Kemi et al., 2005; Swain & Franklin, 2006). Therefore, failing to achieve optimal heart rate-based exercise intensities may result in suboptimal cardioprotective effects. Persistent reductions in energy expenditure due to mental fatigue, even while engaging in regular physical activity, could also have negative implications for weight management. Assuming diet and time spent exercising are held constant, reduced caloric expenditure associated with exercising while mentally-fatigued could lead to gradual weight gain over time. Extrapolated over years, this could result in being overweight or obesity, which are associated with several comorbid conditions known to have a negative impact on quality of life (Jia & Lubetkin, 2005). Consequently, mental fatigue may be an important factor that operates through multiple avenues to pose a significant economic burden on the North American economy each year due to costs associated with increased risk of several chronic conditions (Padula, Allen & Nair, 2014; Tran, Nair, Kuhle, Ohinmaa & Veugelers, 2013).

Despite the implications associated with suboptimal exercise performance that can occur when people are mentally-fatigued, Studies 2 and 4 present practical implications for coping with mental fatigue. Previous research has shown that autonomy supportive feedback (Graham, Bray & Martin Ginis, 2014) and consuming caffeinated products (Azevedo, Silva-Cavalcante, Gualano, Lima-Silva & Bertuzzi, 2016) can counteract the negative effects of mental fatigue on self-regulation of physical activity behaviour. However, people do not always have access to support or feedback from others while exercising and a sizable portion of the population does not consume caffeinated products (Mitchell, Knight, Hockenberry, Teplansky & Hartman, 2014). Findings revealed that incentives (Study 2) and heart rate biofeedback (Study 4) are two promising intervention strategies that people can also adopt to overcome mental fatigue.

Research investigating behaviour change interventions has shown offering incentives such as financial rewards or prizes can modestly increase physical activity levels compared to no-reward/prize control conditions (Dishman, DeJoy, Wilson & Vandenberg, 2009; Mitchell et al., 2013; Robison et al., 1992). However, these studies have not factored in the role of fatigue, which may have been an important moderating factor. Evidence from Study 2 indicates incentives are most effective for motivating behaviour when people are fatigued, whereas those benefits dissipate in a non-fatigued state. These findings may be particularly applicable to workplace physical activity interventions as many occupations involve demanding cognitive tasks and organizations may stand to benefit from preventative spending to incentivize activity in order to reduce costs at a later date (Baicker, Cutler, & Song, 2010). Specifically, organizations should investigate which job requirements render employees at the highest risk of developing symptoms of mental fatigue. This strategy could help to determine who may be at risk, ways in which job parameters could be made less mentally-demanding, and also help determine where resources could be invested to maximize return on cost when implementing incentive-based interventions to motivate employees to be more active. Considering physical activity is crucial for maintaining health and functioning, organizations could decrease costs associated with reduced productivity, absenteeism and healthcare compensation (Baicker et al., 2010; Brown, Gilson, Burton & Brown, 2011).

Although the upside of incentives has been established in Study 2 and elsewhere, it would be remiss not to acknowledge potential drawbacks for using incentives. Specifically, interventionists should be cautious using extrinsic rewards as they may undermine self-determined motivation (Deci, Koestner & Ryan, 1999) and limit long-term maintenance of the intended behaviour. Scaling up incentive-based interventions may also be pose financial challenges. With these issues in mind, more cost-effective strategies should be considered and using intervention strategies that target self-regulatory factors may more practical for fostering behaviour change when facing barriers such as fatigue.

Heart rate biofeedback operates as part of a negative feedback loop process that reinforces adherent exercise behaviour (Study 4). These findings have practical relevance for exercisers, athletes, trainers, coaches and practitioners. For instance, many people's busy schedules often limit exercise/training to the late-day or evening when fatigue levels are highest after a long day at school or work. Monitoring objective biofeedback towards pre-established goals/standards could facilitate behavioural adjustments to optimize performance so that people stand to gain the most from each training session. From a population health standpoint, practitioners could also utilize monitoring devices to guide exercise prescription adherence. Doing so could help people ensure they achieve the appropriate quantity and quality of physical activity (i.e., ≥ 150 mins of MVPA) in accordance with public health recommendations; however, further research is needed to investigate whether biofeedback can be effective in a real-world setting.

Evidence from these studies also has practical relevance for researchers across a range of fields examining behavioural outcomes requiring effort regulation such as resistance or aerobic exercise training studies and cognitive assessments. Although it is common practice for researchers to employ methodological designs to control for factors such as circadian rhythms (Blatter & Cajochen, 2007; Drust, Waterhouse, Atkinson, Edwards & Reilly, 2005), the cognitive demands participants experience leading up to laboratory testing sessions may result in varying degrees of mental fatigue (e.g., having just written a test versus having just had a 2-hour break). In order to control for these effects, researchers should consider measuring mental fatigue using visual analogue scales prior to beginning their studies. Using this quick and reliable measure would provide important information regarding participants' current state of mental fatigue, which could allow researchers to incorporate a brief period of recovery to allow symptoms to subside, defer participation to another time when fatigue may not affect their behaviour, or identify when strategies could be implemented to motivate behaviour (e.g., motivational feedback, caffeine, biofeedback, incentives). Mental fatigue scores could also be included in statistical analyses as a covariate to account for potential differences in outcomes such as cognitive or physical performance.

As a final consideration, the collection of studies within this dissertation also has implications for the recent debate regarding whether or not the ego depletion effect exists (cf. Friese et al., 2018). Findings highlight that the effectiveness of the depleting manipulation depends on its duration and difficulty. For example, findings from Study 1 highlight that the cognitive demands of the experimental manipulation must be potent enough to exceed a critical threshold in order to exhibit performance reductions. Studies 3 and 4 also lend insight into the use of a mental fatigue score as a predictor of performance impairments as both studies revealed comparable scores for accumulated mental fatigue (i.e., Stroop: $M = 256$; AX-CPT: $M = 242$) despite involving different cognitive manipulations and durations (i.e., 50-minute AX-CPT versus 10-minute incongruent Stroop task). These discrepant tasks elicited similar scores on the mental fatigue measure as well as similar aerobic exercise performance impairments (i.e., ~5%). Considered together, these findings raise questions as to whether manipulations failing to demonstrate ego depletion effects were powerful enough in terms of difficulty and/or duration to cause a performance effect to occur or whether creating a certain level of subjective mental fatigue is an important prerequisite for ego depletion effects to be observed.

Limitations and Future Directions

Although this dissertation addressed a number of gaps in the literature, several limitations must be acknowledged. First, findings from the current studies were derived from a fairly homogenous sample of young adults enrolled at a post-secondary institution, which limits generalizability to the broader population. Studies examining the relationship between mental fatigue and physical performance have generally involved adults (e.g., Head et al., 2016; MacMahon et al., 2014; Marcora et al., 2009), with recent research extending to youth athletes (Penna et al., 2018). Considering symptoms of fatigue become more pronounced with age (Butt et al., 2010), current findings may not reflect the magnitude of this effect among samples consisting of middle age and older adults. Moving forward, studies should examine a broader range of ages in order to determine whether age is a moderating factor in the mental fatigue - physical performance relationship.

Second, given the highly controlled nature of these laboratory based studies, another limitation is the cognitive manipulations utilized to induce mental fatigue. Despite involving basic characteristics such as sustained attention and response inhibition that are required for completing cognitively demanding academic and occupational tasks, the Stroop task (Studies 1, 2 and 4) and AX-CPT (Study 3) lack ecological validity as individuals are not exposed to these tasks within their naturalistic environments. Future studies are required to investigate the influence of mental fatigue arising from tasks commonly performed at work or school on exercise motivation, perceptions and behaviour. For example, testing participants following a series of lectures/tutorials or a shift at work would be an important next step to evaluate the ecological validity of the mental fatigue - physical performance relationship. While common cognitive requirements at work or school may not be as difficult or effortful as experimental manipulations such as the Stroop task, it would be interesting to see whether accumulated fatigue associated with prolonged time on tasks in real world settings differs from levels witnessed during brief, laboratory-based cognitive tasks.

A further limitation relates to the limited breadth of the cognitive processes involved in the experimental manipulations employed to induce mental fatigue. While people often perform tasks requiring sustained attention and response inhibition, we also commonly encounter situations in which we need to control our emotional responses such as dealing with a frustrating customer at work. Research has shown that emotion regulation has a medium sized effect on subsequent tasks requiring self-control (*d* = .62; Hagger, Wood, Stiff & Chatzisarantis, 2010) and these effects extend to sport performance (Wagstaff, 2014). Therefore, examining the impact of emotion regulation on physical activity behaviour among non-athletic samples would address a gap in the literature and help determine which cognitive processes elicit the greatest detrimental influence on exercise-related cognitions and behaviour.

Although visual analogue scales have demonstrated validity and reliability for measuring mental fatigue (Wood, Magnello & Jewell, 1990), subjective measures do not provide insight regarding the potential physiological mechanisms underlying these effects. Recent research has begun to incorporate neuroimaging techniques to examine changes within brain regions that may account for the downstream effects of mental fatigue. For instance, Pires and colleagues (2018) conducted the first empirical study to examine neural changes in response to effortful cognitive exertion and looked further at how these changes persist well into exercise performance. Incorporating neuroimaging measures in future studies has the potential to address several unanswered questions. For example, is there a relationship between fatigue-induced alterations in brain activation and changes in pre-exercise cognitions? How long is the latent period for restoration of brain alterations due to fatigue in which physical activity behaviour will no longer be down-regulated? What are the underlying neurophysiological correlates that explain why incentives and biofeedback are more effective in a mentally fatigued state compared to non-fatigued? Answering these questions and many others will open the doors for several exciting new avenues of psychophysiological research.

A final limitation relates to the contrived laboratory setting which transcends the intention – behaviour gap. For the purpose of the research questions at hand, participants were not given the option to quit early or forego exercising (Studies 3 & 4) as would be possible when planning to exercise or exercising during their own leisure time. Rhodes and Dickau (2012) have shown a weak relationship between intentions and behaviour, however it would be worthwhile to determine whether this relationship is altered in magnitude in a state of mental fatigue compared to when people are not fatigued. Moving forward, researchers should examine physical activity behaviour in response to mental fatigue without decision making constraints so that we can get a better understanding of what happens when people have more autonomy over their actions.

Conclusion

This dissertation advances current understanding of the relationship between mental fatigue and physical activity behaviour by conducting systematic examinations of mediating and moderating variables that influence this relationship. Specifically, these results are the first to show that impaired behavioural regulation of exercise performance is dependent on exceeding a critical mental fatigue threshold (Study 1). Fatigue-induced proximal shifts in motivational processes seemed to translate into reductions for exercise performance (Studies 1, 3, & 4). Evidence suggests mental fatigue has a negative effect on of public health guideline based physical activity behaviour among the general population (Studies 3 & 4), potentially resulting in suboptimal health and fitness benefits. Finally, findings revealed incentives (Study 2) and heart rate biofeedback (Study 4) moderate the effect of mental fatigue on physical performance. Collectively, these studies highlight that mental fatigue can negatively affect self-regulation of physical activity behaviour, however, people should be aware that intervention strategies can successfully attenuate these effects.

References

Ampel, B. C., Muraven, M., & Mcnay, E. C. (2018). Mental work requires physical energy: Self-control is neither exception nor exceptional. *Frontiers in Psychology, 9*, 1005. doi:10.3389/fpsyg.2018.01005

Azevedo, R., Silva-Cavalcante, M. D., Gualano, B., Lima-Silva, A. E., & Bertuzzi, R. (2016). Effects of caffeine ingestion on endurance performance in mentally fatigued individuals. *European Journal of Applied Physiology*, *116*, 2293-2303. doi:10.1007/s00421-016-3483-y

Baicker, K., Cutler, D., & Song, Z. (2010). Workplace wellness programs can generate savings. *Health Affairs*, *29*, 304-311. doi:10.1377/hlthaff.2009.0626

Bandura, A. (1997). *Self-efficacy: The exercise of control*. New York, NY: Freeman.

Baumeister, R. F., & Vohs, K. D. (2016). Strength model of self-regulation as limited resource: Assessment, controversies, update. *Advances in Experimental Social Psychology, 54*, 67-127. doi:10.1016/bs.aesp.2016.04.001

Blatter, K., & Cajochen, C. (2007). Circadian rhythms in cognitive performance: methodological constraints, protocols, theoretical underpinnings. *Physiology & Behavior, 90*, 196-208. doi:10.1016/j.physbeh.2006.09.009

Brown, H. E., Gilson, N. D., Burton, N. W., & Brown, W. J. (2011). Does physical activity impact on presenteeism and other indicators of workplace well-being?. *Sports Medicine*, *41*, 249-262. doi:10.2165/11539180-000000000-00000

Butt, Z., Rao, A. V., Lai, J. S., Abernethy, A. P., Rosenbloom, S. K., & Cella, D. (2010). Age-associated differences in fatigue among patients with cancer. *Journal of Pain and Symptom Management*, *40*, 217-223. doi:10.1016/j.jpainsymman.2009.12.016

Carver, C. S., & Scheier, M. F. (1982). Control theory: A useful conceptual framework for personality–social, clinical, and health psychology. *Psychological Bulletin*, *92*, 111-135. doi:10.1037/0033-2909.92.1.111

Clarke, T. C., Norris, T., & Schiller, J. S. (2017). Early release of selected estimates based on data from 2016 National Health Interview Survey. *National Center for Health Statistics.*

Deci, E. L., Koestner, R., & Ryan, R. M. (1999). A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation. *Psychological Bulletin*, *125*, 627-668. doi:10.1037//0033-2909.125.6.627

Dishman, R. K., DeJoy, D. M., Wilson, M. G., & Vandenberg, R. J. (2009). Move to Improve: a randomized workplace trial to increase physical activity. *American Journal of Preventive Medicine, 36*, 133-141. doi:10.1016/j.amepre.2008.09.038

Drust, B., Waterhouse, J., Atkinson, G., Edwards, B., & Reilly, T. (2005). Circadian rhythms in sports performance—an update. *Chronobiology International*, *22*, 21-44. doi:10.1081/CBI-200041039

Friese, M., Loschelder, D. D., Gieseler, K., Frankenbach, J., & Inzlicht, M. (2018). Is ego depletion real? An analysis of arguments. *Personality and Social Psychology Review*. Advance online publication. doi: 10.1177/1088868318762

Graham, J. D., & Bray, S. R. (2015). Self-control strength depletion reduces self-efficacy and impairs exercise performance. *Journal of Sport and Exercise Psychology*, *37*, 477-488. doi:10.1123/jsep.2015-0064

Graham, J.D., Bray, S.R., & Martin Ginis, K.A. (2014). “Pay the piper”: It helps initially, but motivation takes a toll on self-control. *Psychology of Sport and Exercise, 15*, 89–96. doi:10.1016/j.psychsport.2013.09.007

Hagger, M. S., Wood, C., Stiff, C., & Chatzisarantis, N. L. (2010). Ego depletion and the strength model of self-control: a meta-analysis. *Psychological Bulletin*, *136*, 495-525. doi:10.1037/a0019486

Head, J. R., Tenan, M. S., Tweedell, A. J., Price, T. F., LaFiandra, M. E., & Helton, W. S. (2016). Cognitive fatigue influences time-on-task during bodyweight resistance training exercise. *Frontiers in Physiology*, *7*, 373. doi:10.3389/fphys.2016.00373

Inzlicht, M., & Schmeichel, B. J. (2012). What is ego depletion? Toward a mechanistic revision of the resource model of self-control. *Perspectives on Psychological Science, 7*, 450-463. doi:10.1177/1745691612454134

Inzlicht, M., & Schmeichel, B. J. (2016). Beyond limited resources: Self-control failure as the product of shifting priorities. In K. D. Vohs & R. F Baumeister (3rd ed.), *Handbook of self-regulation: Research, theory, and applications* (pp. 165-181). New York, NY: Guilford Press.

Inzlicht, M., Schmeichel, B. J., & Macrae, C. N. (2014). Why self-control seems (but may not be) limited. *Trends in Cognitive Sciences*, *18*, 127-133. doi:10.1016/j.tics.2013.12.009

Jia, H., & Lubetkin, E. I. (2005). The impact of obesity on health-related quality-of-life in the general adult US population. *Journal of Public Health*, *27*, 156-164. doi:10.1093/pubmed/fdi025

Kemi, O. J., Haram, P. M., Loennechen, J. P., Osnes, J. B., Skomedal, T., Wisløff, U., & Ellingsen, Ø. (2005). Moderate vs. high exercise intensity: differential effects on aerobic fitness, cardiomyocyte contractility, and endothelial function. *Cardiovascular Research*, *67*, 161-172.

Kotabe, H. P., & Hofmann, W. (2015). On integrating the components of self-control. *Perspectives on Psychological Science*, *10*, 618-638. doi:10.1177/1745691615593382

Kurzban, R., Duckworth, A., Kable, J. W., & Myers, J. (2013). An opportunity cost model of subjective effort and task performance. *Behavioral and Brain Sciences*, *36*, 661-679. doi:10.1017/s0140525x12003196

Luethi, M.S., Friese, M., Binder, J., Boesiger, P., Luechinger, R., & Rasch, B. (2016).Motivational incentives lead to a strong increase in lateral prefrontal activity after self-control exertion. *Social Cognitive and Affective Neuroscience, 11*, 1618–1626. doi:10.1093/scan/nsw073

MacMahon, C., Schücker, L., Hagemann, N., & Strauss, B. (2014). Cognitive fatigue effects on physical performance during running. *Journal of Sport and Exercise Psychology, 36*, 375-381. doi:10.1123/jsep.2013-0249

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *Journal of Applied Physiology, 106*, 857-864. doi:10.1152/japplphysiol.91324.2008

Martin Ginis, K. A., & Bray, S. R. (2010). Application of the limited strength model of self-regulation to understanding exercise effort, planning and adherence. *Psychology and Health, 25*, 1147-1160. doi:10.1080/08870440903111696

Micklewright, D., St. Clair Gibson, A., Gladwell, V., & Al Salman, A. (2017). Development and validity of the rating-of-fatigue scale. *Sports Medicine*, *47*, 2375-2393. doi:10.1007/s40279-017-0711-5

Milyavskaya, M., & Inzlicht, M. (2017). What's so great about self-control? Examining the importance of effortful self-control and temptation in predicting real-life depletion and goal attainment. *Social Psychological and Personality Science, 8*, 603-611. doi:10.1177/1948550616679237

Mitchell, M. S., Goodman, J. M., Alter, D. A., John, L. K., Oh, P. I., Pakosh, M. T., & Faulkner, G. E. (2013). Financial incentives for exercise adherence in adults: systematic review and meta-analysis. *American Journal of Preventive Medicine*, *45*, 658-667. doi:10.1016/j.amepre.2013.06.017

Mitchell, D. C., Knight, C. A., Hockenberry, J., Teplansky, R., & Hartman, T. J. (2014). Beverage caffeine intakes in the US. *Food and Chemical Toxicology*, *63*, 136-142. doi:10.1016/j.fct.2013.10.042

Müller, T. & Apps, M. A. (In Press). Motivational fatigue: A neurocognitive framework for the impact of effortful exertion on subsequent motivation. *Neuropsychologia*. Advance online publication. doi:10.1016/j.neuropsychologia.2018.04.030

Muraven, M., & Slessareva, E. (2003). Mechanisms of self-control failure: Motivation and limited resources. Personality and Social Psychology Bulletin, 29, 894–906. doi:10.1177/0146167203029007008

Padula, W. V., Allen, R. R., & Nair, K. V. (2014). Determining the cost of obesity and its common comorbidities from a commercial claims database. *Clinical Obesity, 4*, 53-58. doi: 10.1111/cob.12041

Penna, E. M., Filho, E., Wanner, S. P., Campos, B. T., Quinan, G. R., Mendes, T. T., ... & Prado, L. S. (2018). Mental fatigue impairs physical performance in young swimmers. *Pediatric Exercise Science, 30*, 208-215. doi.org/10.1123/pes.2017-0128

Pires, F. O., Silva-Júnior, F. L., Brietzke, C., Franco-Alvarenga, P. E., Pinheiro, F. A., de França, N. M., ... & Meireles Santos, T. (2018). Mental fatigue alters cortical activation and psychological responses, impairing performance in a distance-based cycling trial. *Frontiers in Physiology, 9*, 227. doi:10.3389/fphys.2018.00227

Public Health Agency of Canada (2016). *Health status of Canadians 2016*. Government of Canada.

Rhodes, R. E., & Dickau, L. (2012). Experimental evidence for the intention–behavior relationship in the physical activity domain: A meta-analysis. *Health Psychology*, *31,* 724-727. doi:10.1037/a0027290

Robison, J. I., Rogers, M. A., Carlson, J. J., Mavis, B. E., Stachnik, T., Stoffelmayr, B., ... & Van Huss, W. D. (1992). Effects of a 6-month incentive-based exercise program on adherence and work capacity. *Medicine & Science in Sports & Exercise, 24,* 85-93. doi:10.1249/00005768-199201000-00015

Salmon, J., Owen, N., Crawford, D., Bauman, A., & Sallis, J. F. (2003). Physical activity and sedentary behavior: a population-based study of barriers, enjoyment, and preference. *Health Psychology, 22,* 178-188. doi:10.1037//0278-6133.22.2.178

Swain, D. P., & Franklin, B. A. (2006). Comparison of cardioprotective benefits of vigorous versus moderate intensity aerobic exercise. *American Journal of Cardiology*, *97*, 141-147. doi:10.1016/j.amjcard.2005.07.130

Tran, B. X., Nair, A. V., Kuhle, S., Ohinmaa, A., & Veugelers, P. J. (2013). Cost analyses of obesity in Canada: scope, quality, and implications. *Cost Effectiveness and Resource Allocation*, *11*, 3. doi:10.1186/1478-7547-11-3

vanDellen, M. R., Hoyle, R. H., & Miller, R. (2012). The regulatory easy street: Self-regulation below the self-control threshold does not consume regulatory resources. *Personality and Individual Differences, 52,* 898-902. doi:10.1016/j.paid.2012.01.028

Wagstaff, C. R. (2014). Emotion regulation and sport performance. *Journal of Sport and Exercise Psychology*, *36*, 401-412. doi:10.1123/jsep.2013-0257

Wood, C., Magnello, M. E., & Jewell, T. (1990). Measuring vitality. *Journal of the Royal Society of Medicine, 83,* 486-489. doi:10.1177/014107689008300803

APPENDIX A: STUDY 1 MATERIALS

A.1 International Physical Activity Questionnaire
A.2 Physical Activity Readiness Questionnaire
A.2 Task Self-Efficacy Scale
A.3 Ratings of Perceived Physical Exertion Scale
A.4 Mental Fatigue Visual Analogue Scale
A.5 The Feeling Scale
A.6 Task Motivation Visual Analogue Scale
A.7 Intrinsic Motivation Inventory Effort and Importance Subscale

Appendix A.1:
International Physical Activity Questionnaire

How active are you usually? Please consider your usual activity level during a typical 7 day period in the past 6 months and answer the following about moderate and vigorous activity participation.

MODERATE Physical Activity Definition
Moderate physical activity or exercise includes activities such as brisk walking, light swimming, dancing, biking, gardening, and yardwork. You should be able to carry on a conversation when doing moderate activities. Please consider a TYPICAL week for you and answer the following questions about moderate activities.

1. How many days per week are you moderately physically active or do you exercise moderately?

_____ days per week

2. Approximately how many minutes are you moderately physically active or do you exercise moderately each day?

_____ minutes per day

VIGOROUS Physical Activity Definition:

Vigorous physical activity or exercise includes hard activities such as jogging, aerobics, swimming, and fast biking. You may have a hard time carrying on a conversation when doing vigorous activities. Please consider a TYPICAL week for you and answer the following questions about vigorous activities.

1. How many days per week are you vigorously active or do you exercise vigorously?

_____ days per week

2. Approximately how many minutes are you vigorously active or do you exercise vigorously each day?

_____ minutes per day

Appendix A.2
Physical Activity Readiness Questionnaire

You are eligible for this study if you answer **NO** to the questions below

1. Do you have a medical condition that requires you to avoid strenuous exercise?

2. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

3. Do you feel pain in your chest when you do physical activity?

4. In the past month, have you had chest pain when you were not doing physical activity?

5. Do you lose balance because of dizziness or do you lose consciousness?

6. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?

7. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

8. Do you know of any other reason why you should not do physical activity?

9. Are you colour blind?

Appendix A.3
Task Self-Efficacy Scale

Compared to how long I went last time I am confident that I can hold on for:

Performance Rating	**Yes/No (Y or N)**	**Strength 0-10**
A) 25% as long		
B) 50% as long (half the time)		
C) 75% as long		
D) 100% as long (the same amount)		
E) 125% as long		
F) 150% as long		
G) 175% as long		
H) 200% as long (double the amount)		

Appendix A.4
Ratings of Perceived Physical Exertion Scale

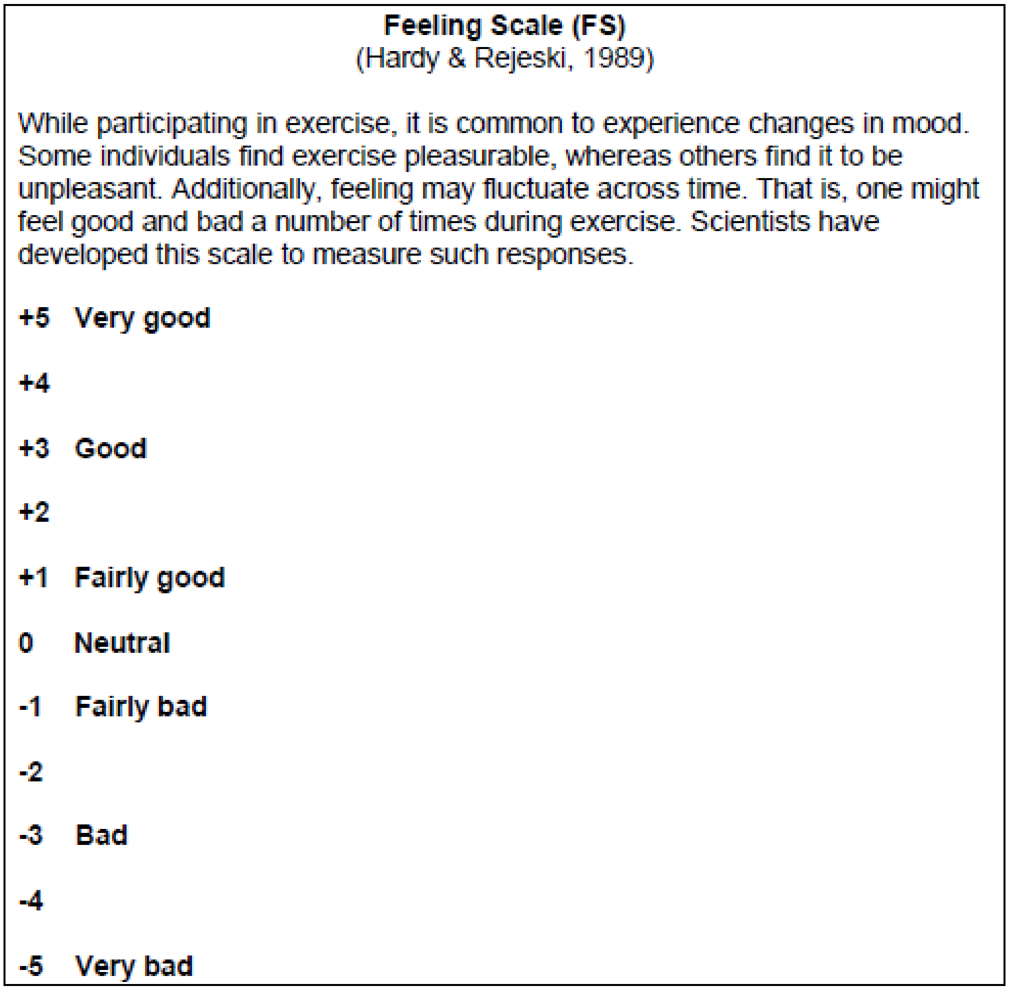
0	Nothing at all
0.3	
0.5	Extremely weak
1	Very weak
1.5	
2	Weak
2.5	
3	Moderate
4	
5	Strong
6	
7	Very Strong
8	
9	
10	Absolute Maximum

Appendix A.5
Mental Fatigue Visual Analogue Scale

Please mark (X) on the line the point that you feel represents your perception of your current state of **MENTAL FATIGUE**.

None at all 0
____ 100
Maximal

Appendix A.6
Feeling Scale



Feeling Scale (FS)
(Hardy & Rejeski, 1989)

While participating in exercise, it is common to experience changes in mood. Some individuals find exercise pleasurable, whereas others find it to be unpleasant. Additionally, feeling may fluctuate across time. That is, one might feel good and bad a number of times during exercise. Scientists have developed this scale to measure such responses.

+5	**Very good**
+4	
+3	**Good**
+2	
+1	**Fairly good**
0	**Neutral**
-1	**Fairly bad**
-2	
-3	**Bad**
-4	
-5	**Very bad**

Appendix A.7
Task Motivation Visual Analogue Scale

For the upcoming Handgrip task:

Please mark (X) on the line the point that you feel represents your perception of your current state of **MOTIVATION**.

None at all 0
____ 100
Maximal

Appendix A.8
Intrinsic Motivation Inventory Effort and Importance Subscale

For each of the following statements, please indicate how true it is for you, using the following scale:

1	**2**	**3**	**4**	**5**	**6**	**7**
Not at all true			**Somewhat true**			**Very true**

For handgrip squeezing task I am about to do:

1. I am going to put a lot of effort into this. ______
2. I am not going to try very hard to do well at this activity. ______
3. I am going to try very hard on this activity. ______
4. It is important to me to do well at this task. ______
5. I am not going to put much energy into this. ______

APPENDIX B: STUDY 2 MATERIALS

B.1 International Physical Activity Questionnaire
B.2 Physical Activity Readiness Questionnaire
B.3 Brief Self-Control Scale
B.4 Ratings of Perceived Physical Exertion Scale
B.5 Task Motivation Visual Analogue Scale
B.6 Mental Fatigue Visual Analogue Scale

Appendix B.1:
International Physical Activity Questionnaire

How active are you usually? Please consider your usual activity level during a typical 7 day period in the past 6 months and answer the following about moderate and vigorous activity participation.

MODERATE Physical Activity Definition

Moderate physical activity or exercise includes activities such as brisk walking, light swimming, dancing, biking, gardening, and yardwork. You should be able to carry on a conversation when doing moderate activities. Please consider a TYPICAL week for you and answer the following questions about moderate activities.

1. How many days per week are you moderately physically active or do you exercise moderately?

_____ days per week

2. Approximately how many minutes are you moderately physically active or do you exercise moderately each day?

_____ minutes per day

VIGOROUS Physical Activity Definition:

Vigorous physical activity or exercise includes hard activities such as jogging, aerobics, swimming, and fast biking. You may have a hard time carrying on a conversation when doing vigorous activities. Please consider a TYPICAL week for you and answer the following questions about vigorous activities.

1. How many days per week are you vigorously active or do you exercise vigorously?

_____ days per week

2. Approximately how many minutes are you vigorously active or do you exercise vigorously each day?

_____ minutes per day

Appendix B.2
Physical Activity Readiness Questionnaire

You are eligible for this study if you answer **NO** to the questions below

1. Do you have a medical condition that requires you to avoid strenuous exercise?

2. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

3. Do you feel pain in your chest when you do physical activity?

4. In the past month, have you had chest pain when you were not doing physical activity?

5. Do you lose balance because of dizziness or do you lose consciousness?

6. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?

7. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

8. Do you know of any other reason why you should not do physical activity?

9. Are you colour blind?

Appendix B.3
Brief Self-Control Scale

SCS Scale

Please answer the following items as they apply to you. There are no right or wrong answers. Please choose a number (1 – 5) that best represents what you believe to be true about yourself for each question. Use the following scale to refer to how much each question is true about you.

1	2	3	4	5
Not at all like me		**Sometimes like me**		**Very Much like me**

1. I have a hard time breaking bad habits. _____

2. I am lazy. _____

3. I say inappropriate things. _____

4. I do certain things that are bad for me, if they are fun. _____

5. I refuse things that are bad for me. _____

6. I wish I had more self-discipline. _____

7. People would say that I have iron self-discipline. _____

8. Pleasure and fun sometimes keep me from getting work done. _____

9. I have trouble concentrating. _____

10. I am able to work effectively toward long-term goals. _____

11. Sometimes I can’t stop myself from doing something, even if I know it’s wrong. ____

12. I often act without thinking through all the alternatives. _____

13. I am good at resisting temptation. _____

Appendix B.4
Ratings of Perceived Physical Exertion Scale

0	Nothing at all
0.3	
0.5	Extremely weak
1	Very weak
1.5	
2	Weak
2.5	
3	Moderate
4	
5	Strong
6	
7	Very Strong
8	
9	
10	Absolute Maximum

Appendix B.5
Task Motivation Visual Analogue Scale

For the upcoming Handgrip task:

Please mark (X) on the line the point that you feel represents your perception of your current state of **MOTIVATION**.

None at all 0
____ 100
Maximal

Appendix B.6
Mental Fatigue Visual Analogue Scale

Please mark (X) on the line the point that you feel represents your perception of your current state of **MENTAL FATIGUE**.

None at all 0
____ 100
Maximal

APPENDIX C: STUDY 3 MATERIALS

Appendix C.1:
International Physical Activity Questionnaire

How active are you usually? Please consider your usual activity level during a typical 7 day period in the past 6 months and answer the following about moderate and vigorous activity participation.

MODERATE Physical Activity Definition

Moderate physical activity or exercise includes activities such as brisk walking, light swimming, dancing, biking, gardening, and yardwork. You should be able to carry on a conversation when doing moderate activities. Please consider a TYPICAL week for you and answer the following questions about moderate activities.

1. How many days per week are you moderately physically active or do you exercise moderately?

_____ days per week

2. Approximately how many minutes are you moderately physically active or do you exercise moderately each day?

_____ minutes per day

VIGOROUS Physical Activity Definition:

Vigorous physical activity or exercise includes hard activities such as jogging, aerobics, swimming, and fast biking. You may have a hard time carrying on a conversation when doing vigorous activities. Please consider a TYPICAL week for you and answer the following questions about vigorous activities.

1. How many days per week are you vigorously active or do you exercise vigorously?

_____ days per week

2. Approximately how many minutes are you vigorously active or do you exercise vigorously each day?

_____ minutes per day

Appendix C.2
Physical Activity Readiness Questionnaire

You are eligible for this study if you answer **NO** to the questions below

1. Do you have a medical condition that requires you to avoid strenuous exercise?

2. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

3. Do you feel pain in your chest when you do physical activity?

4. In the past month, have you had chest pain when you were not doing physical activity?

5. Do you lose balance because of dizziness or do you lose consciousness?

6. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?

7. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

8. Do you know of any other reason why you should not do physical activity?

9. Are you colour blind?

Appendix C.3
Mental Fatigue Visual Analogue Scale

Please mark (X) on the line the point that you feel represents your perception of your current state of **MENTAL FATIGUE**.

None at all 0
____ 100
Maximal

Appendix C.4
Intended Physical Exertion

Please circle the RPE you plan to exercise at during the upcoming exercise session.

How hard the exercise feels to do

	RPE	
	20	Maximal exertion
	19	Extremely hard
	18	
ACSM Physical Activity Recommendation Target Zone	17	Very hard
	16	
	15	Hard
	14	
	13	Somewhat hard
	12	Moderate
	11	Light
	10	
	9	Very light
	8	
	7	Very, very light
	6	No exertion at all

Appendix C.5
Task Motivation Visual Analogue Scale

For the upcoming exercise task:

Please mark (X) on the line the point that you feel represents your perception of your current state of **MOTIVATION**.

None at all 0
____ 100
Maximal

APPENDIX D: STUDY 4 MATERIALS

D.1 International Physical Activity Questionnaire
D.2 Physical Activity Readiness Questionnaire
D.3 National Aeronautics and Space Administration Task Load Index (NASA TLX) – Mental Demand Subscale
D.4 Mental Fatigue Visual Analogue Scale
D.5 Intrinsic Motivation Inventory Effort and Importance Subscale
D.6 Task Motivation Visual Analogue Scale
D.7 Intended Physical Exertion Scale
D.8 Goal Commitment Scale
D.9 Rating of Perceived Exertion Scale

Appendix D.1
International Physical Activity Questionnaire

How active are you usually? Please consider your usual activity level during a typical 7 day period in the past 6 months and answer the following about moderate and vigorous activity participation.

MODERATE Physical Activity Definition

Moderate physical activity or exercise includes activities such as brisk walking, light swimming, dancing, biking, gardening, and yardwork. You should be able to carry on a conversation when doing moderate activities. Please consider a TYPICAL week for you and answer the following questions about moderate activities.

1. How many days per week are you moderately physically active or do you exercise moderately?

_____ days per week

2. Approximately how many minutes are you moderately physically active or do you exercise moderately each day?

_____ minutes per day

VIGOROUS Physical Activity Definition:

Vigorous physical activity or exercise includes hard activities such as jogging, aerobics, swimming, and fast biking. You may have a hard time carrying on a conversation when doing vigorous activities. Please consider a TYPICAL week for you and answer the following questions about vigorous activities.

1. How many days per week are you vigorously active or do you exercise vigorously?

_____ days per week

2. Approximately how many minutes are you vigorously active or do you exercise vigorously each day?

_____ minutes per day

Appendix D.2
Physical Activity Readiness Questionnaire

You are eligible for this study if you answer **NO** to the questions below

1. Do you have a medical condition that requires you to avoid strenuous exercise?

2. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?

3. Do you feel pain in your chest when you do physical activity?

4. In the past month, have you had chest pain when you were not doing physical activity?

5. Do you lose balance because of dizziness or do you lose consciousness?

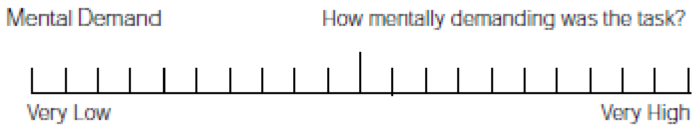
6. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?

7. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?

8. Do you know of any other reason why you should not do physical activity?

9. Are you colour blind?

Appendix D.3
NASA-TLX - Mental Demand Subscale



Mental Demand

How mentally demanding was the task?

Very Low

Very High

Appendix D.4
Mental Fatigue Visual Analogue Scale

Please mark (X) on the line the point that you feel represents your perception of your current state of **MENTAL FATIGUE**.

None at all 0

____ 100

Maximal

Appendix D.5
Intrinsic Motivation Inventory Effort and Importance Subscale

For each of the following statements, please indicate how true it is for you, using the following scale:

1 2 3 4 5 6 7

Not true **Very true**

For exercise task I am about to do:

1. I am going to put a lot of effort into this. ______
2. I am **not** going to try very hard to do well at this activity. ______
3. I am going to try very hard on this activity. ______
4. It is important to me to do well at this task. ______
5. I am **not** going to put much energy into this. ______

Appendix D.6

Task Motivation Visual Analogue Scale

For the upcoming exercise task:

Please mark (X) on the line the point that you feel represents your perception of your current state of **MOTIVATION**.

None at all 0
____ 100
Maximal

Appendix D.7
Intended Physical Exertion

Please circle the RPE you plan to exercise at during the upcoming exercise session.

How hard the exercise feels to do

	RPE	
	20	Maximal exertion
	19	Extremely hard
	18	
ACSM Vigorous-Intensity Recommendation Target Zone	17	Very hard
	16	
	15	Hard
	14	
ACSM Moderate-Intensity Recommendation Target Zone	13	Somewhat hard
	12	Moderate
	11	Light
	10	
	9	Very light
	8	
	7	Very, very light
	6	No exertion at all

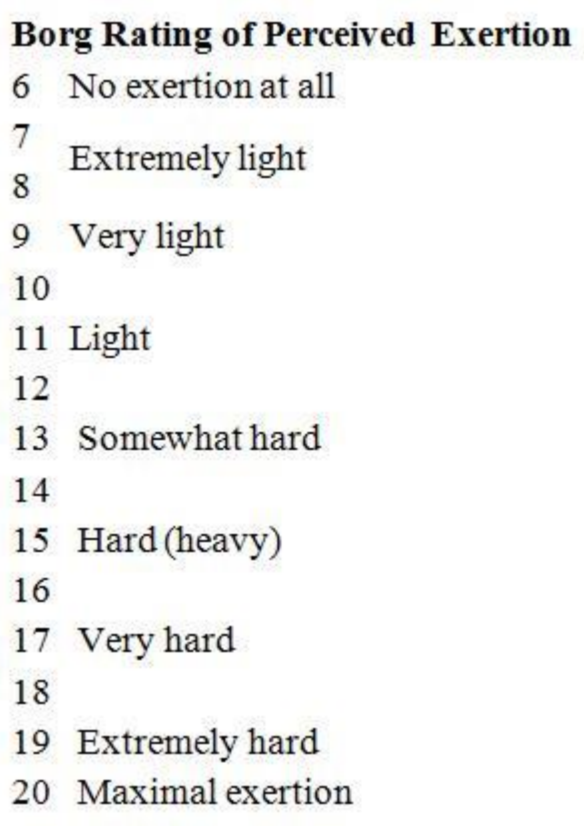
Appendix C.8
Goal Commitment Scale

Please answer the following items as they apply to you. There are no right or wrong answers. Please complete the measure with regard to only the assigned goal level of exercising at a vigorous-intensity (RPE 14-17).

1	**2**	**3**	**4**	**5**
Strongly Agree		**Moderately Agree**		**Strongly Disagree**

1. It’s hard to take this goal seriously. ____
2. Quite frankly, I don’t care if I achieve this goal or not. ____
3. I am strongly committed to pursuing this goal. ____
4. It wouldn’t take much for me to abandon this goal. ____
5. I think this is a good goal to shoot for. ____

Appendix C.9
Rating of Perceived Exertion Scale

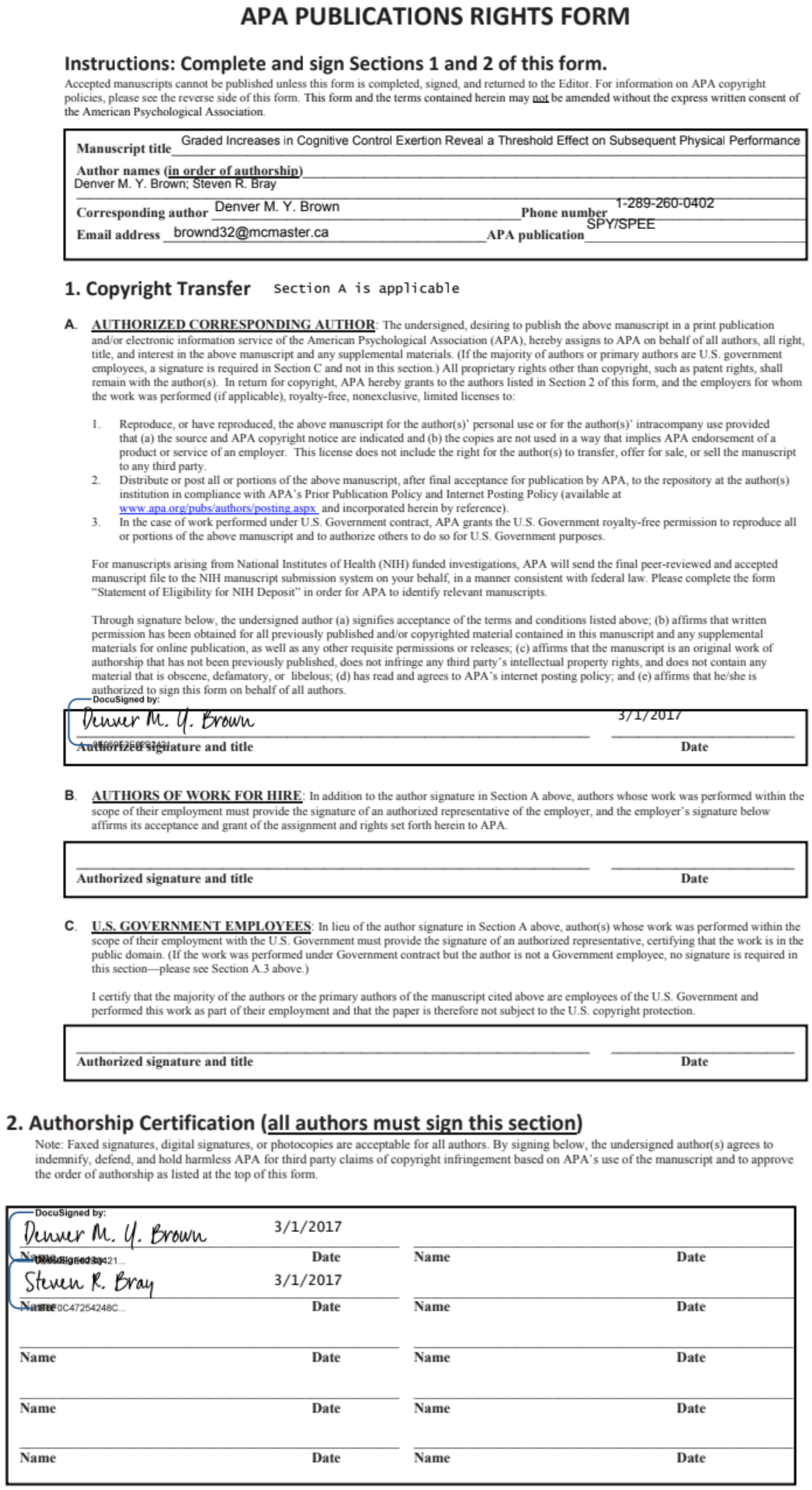


Borg Rating of Perceived Exertion

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

APPENDIX E: COPYRIGHT PERMISSIONS

Appendix E.1
Permission from the American Psychology Association (Chapter 2)



APA PUBLICATIONS RIGHTS FORM

Instructions: Complete and sign Sections 1 and 2 of this form.

Accepted manuscripts cannot be published unless this form is completed, signed, and returned to the Editor. For information on APA copyright policies, please see the reverse side of this form. This form and the terms contained herein may not be amended without the express written consent of the American Psychological Association.

Manuscript title Graded Increases in Cognitive Control Exertion Reveal a Threshold Effect on Subsequent Physical Performance
Author names (in order of authorship) Denver M. Y. Brown; Steven R. Bray
Corresponding author Denver M. Y. Brown **Phone number** 1-289-260-0402
Email address brownd32@mcmaster.ca **APA publication** SPY/SPEE

1. Copyright Transfer

Section A is applicable

A. **AUTHORIZED CORRESPONDING AUTHOR**: The undersigned, desiring to publish the above manuscript in a print publication and/or electronic information service of the American Psychological Association (APA), hereby assigns to APA on behalf of all authors, all right, title, and interest in the above manuscript and any supplemental materials. (If the majority of authors or primary authors are U.S. government employees, a signature is required in Section C and not in this section.) All proprietary rights other than copyright, such as patent rights, shall remain with the author(s). In return for copyright, APA hereby grants to the authors listed in Section 2 of this form, and the employers for whom the work was performed (if applicable), royalty-free, nonexclusive, limited licenses to:

1. Reproduce, or have reproduced, the above manuscript for the author(s)' personal use or for the author(s)' intracompany use provided that (a) the source and APA copyright notice are indicated and (b) the copies are not used in a way that implies APA endorsement of a product or service of an employer. This license does not include the right for the author(s) to transfer, offer for sale, or sell the manuscript to any third party.
2. Distribute or post all or portions of the above manuscript, after final acceptance for publication by APA, to the repository at the author(s) institution in compliance with APA's Prior Publication Policy and Internet Posting Policy (available at www.apa.org/pubs/authors/posting.aspx and incorporated herein by reference).
3. In the case of work performed under U.S. Government contract, APA grants the U.S. Government royalty-free permission to reproduce all or portions of the above manuscript and to authorize others to do so for U.S. Government purposes.

For manuscripts arising from National Institutes of Health (NIH) funded investigations, APA will send the final peer-reviewed and accepted manuscript file to the NIH manuscript submission system on your behalf, in a manner consistent with federal law. Please complete the form "Statement of Eligibility for NIH Deposit" in order for APA to identify relevant manuscripts.

Through signature below, the undersigned author (a) signifies acceptance of the terms and conditions listed above; (b) affirms that written permission has been obtained for all previously published and/or copyrighted material contained in this manuscript and any supplemental materials for online publication, as well as any other requisite permissions or releases; (c) affirms that the manuscript is an original work of authorship that has not been previously published, does not infringe any third party's intellectual property rights, and does not contain any material that is obscene, defamatory, or libelous; (d) has read and agrees to APA's internet posting policy; and (e) affirms that he/she is authorized to sign this form on behalf of all authors.

DocuSigned by:
Denver M. Y. Brown 3/1/2017
Authorized signature and title **Date**

B. **AUTHORS OF WORK FOR HIRE**: In addition to the author signature in Section A above, authors whose work was performed within the scope of their employment must provide the signature of an authorized representative of the employer, and the employer's signature below affirms its acceptance and grant of the assignment and rights set forth herein to APA.

Authorized signature and title **Date**

C. **U.S. GOVERNMENT EMPLOYEES**: In lieu of the author signature in Section A above, author(s) whose work was performed within the scope of their employment with the U.S. Government must provide the signature of an authorized representative, certifying that the work is in the public domain. (If the work was performed under Government contract but the author is not a Government employee, no signature is required in this section—please see Section A.3 above.)

I certify that the majority of the authors or the primary authors of the manuscript cited above are employees of the U.S. Government and performed this work as part of their employment and that the paper is therefore not subject to the U.S. copyright protection.

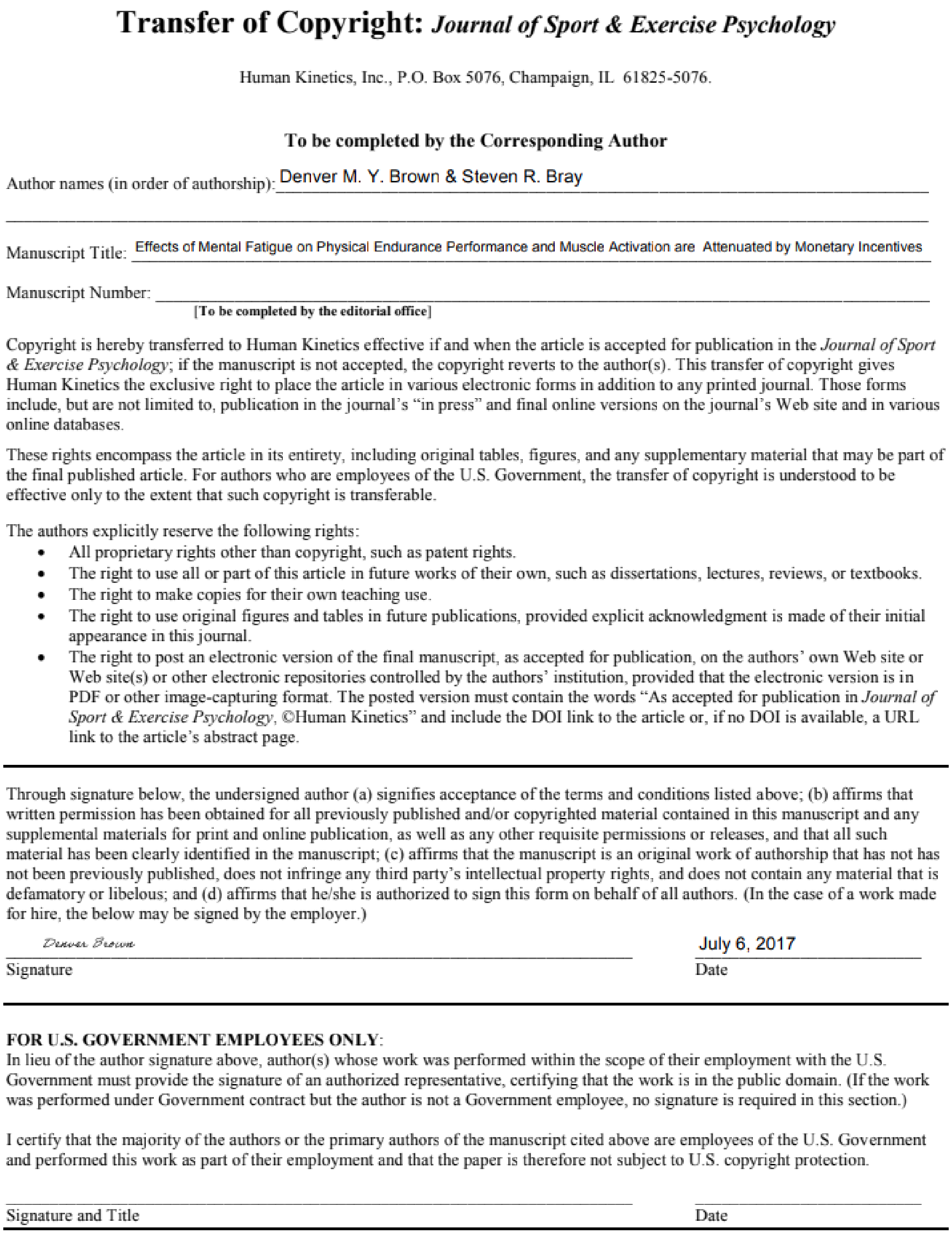
Authorized signature and title **Date**

2. Authorship Certification (all authors must sign this section)

Note: Faxed signatures, digital signatures, or photocopies are acceptable for all authors. By signing below, the undersigned author(s) agrees to indemnify, defend, and hold harmless APA for third party claims of copyright infringement based on APA's use of the manuscript and to approve the order of authorship as listed at the top of this form.

DocuSigned by: Denver M. Y. Brown	3/1/2017		
Name	**Date**	**Name**	**Date**
DocuSigned by: Steven R. Bray	3/1/2017		
Name	**Date**	**Name**	**Date**
Name	**Date**	**Name**	**Date**
Name	**Date**	**Name**	**Date**
Name	**Date**	**Name**	**Date**

Appendix E.2
Permission from Human Kinetics (Chapter 3)



Transfer of Copyright: *Journal of Sport & Exercise Psychology*

Human Kinetics, Inc., P.O. Box 5076, Champaign, IL 61825-5076.

To be completed by the Corresponding Author

Author names (in order of authorship): Denver M. Y. Brown & Steven R. Bray

Manuscript Title: Effects of Mental Fatigue on Physical Endurance Performance and Muscle Activation are Attenuated by Monetary Incentives

Manuscript Number:
[To be completed by the editorial office]

Copyright is hereby transferred to Human Kinetics effective if and when the article is accepted for publication in the *Journal of Sport & Exercise Psychology*; if the manuscript is not accepted, the copyright reverts to the author(s). This transfer of copyright gives Human Kinetics the exclusive right to place the article in various electronic forms in addition to any printed journal. Those forms include, but are not limited to, publication in the journal's "in press" and final online versions on the journal's Web site and in various online databases.

These rights encompass the article in its entirety, including original tables, figures, and any supplementary material that may be part of the final published article. For authors who are employees of the U.S. Government, the transfer of copyright is understood to be effective only to the extent that such copyright is transferable.

The authors explicitly reserve the following rights:

- All proprietary rights other than copyright, such as patent rights.
- The right to use all or part of this article in future works of their own, such as dissertations, lectures, reviews, or textbooks.
- The right to make copies for their own teaching use.
- The right to use original figures and tables in future publications, provided explicit acknowledgment is made of their initial appearance in this journal.
- The right to post an electronic version of the final manuscript, as accepted for publication, on the authors' own Web site or Web site(s) or other electronic repositories controlled by the authors' institution, provided that the electronic version is in PDF or other image-capturing format. The posted version must contain the words "As accepted for publication in *Journal of Sport & Exercise Psychology*, ©Human Kinetics" and include the DOI link to the article or, if no DOI is available, a URL link to the article's abstract page.

Through signature below, the undersigned author (a) signifies acceptance of the terms and conditions listed above; (b) affirms that written permission has been obtained for all previously published and/or copyrighted material contained in this manuscript and any supplemental materials for print and online publication, as well as any other requisite permissions or releases, and that all such material has been clearly identified in the manuscript; (c) affirms that the manuscript is an original work of authorship that has not has not been previously published, does not infringe any third party's intellectual property rights, and does not contain any material that is defamatory or libelous; and (d) affirms that he/she is authorized to sign this form on behalf of all authors. (In the case of a work made for hire, the below may be signed by the employer.)

Denver Brown
Signature

July 6, 2017
Date

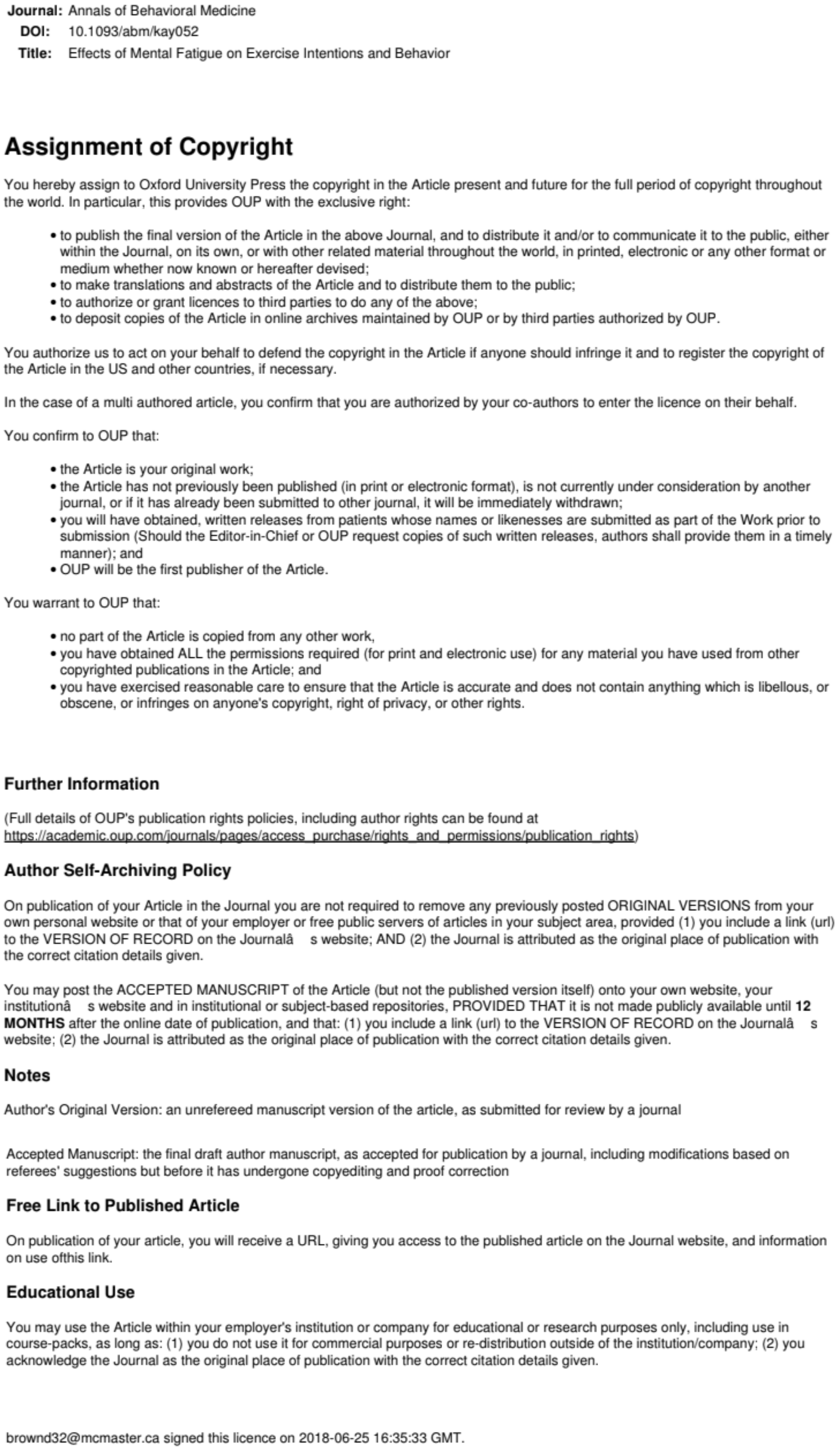
FOR U.S. GOVERNMENT EMPLOYEES ONLY:
In lieu of the author signature above, author(s) whose work was performed within the scope of their employment with the U.S. Government must provide the signature of an authorized representative, certifying that the work is in the public domain. (If the work was performed under Government contract but the author is not a Government employee, no signature is required in this section.)

I certify that the majority of the authors or the primary authors of the manuscript cited above are employees of the U.S. Government and performed this work as part of their employment and that the paper is therefore not subject to U.S. copyright protection.

Signature and Title

Date

Appendix E.3
Permission from Oxford University Press (Chapter 4)



Journal: Annals of Behavioral Medicine
DOI: 10.1093/abm/kay052
Title: Effects of Mental Fatigue on Exercise Intentions and Behavior

Assignment of Copyright

You hereby assign to Oxford University Press the copyright in the Article present and future for the full period of copyright throughout the world. In particular, this provides OUP with the exclusive right:

- to publish the final version of the Article in the above Journal, and to distribute it and/or to communicate it to the public, either within the Journal, on its own, or with other related material throughout the world, in printed, electronic or any other format or medium whether now known or hereafter devised;
- to make translations and abstracts of the Article and to distribute them to the public;
- to authorize or grant licences to third parties to do any of the above;
- to deposit copies of the Article in online archives maintained by OUP or by third parties authorized by OUP.

You authorize us to act on your behalf to defend the copyright in the Article if anyone should infringe it and to register the copyright of the Article in the US and other countries, if necessary.

In the case of a multi authored article, you confirm that you are authorized by your co-authors to enter the licence on their behalf.

You confirm to OUP that:

- the Article is your original work;
- the Article has not previously been published (in print or electronic format), is not currently under consideration by another journal, or if it has already been submitted to other journal, it will be immediately withdrawn;
- you will have obtained, written releases from patients whose names or likenesses are submitted as part of the Work prior to submission (Should the Editor-in-Chief or OUP request copies of such written releases, authors shall provide them in a timely manner); and
- OUP will be the first publisher of the Article.

You warrant to OUP that:

- no part of the Article is copied from any other work,
- you have obtained ALL the permissions required (for print and electronic use) for any material you have used from other copyrighted publications in the Article; and
- you have exercised reasonable care to ensure that the Article is accurate and does not contain anything which is libellous, or obscene, or infringes on anyone's copyright, right of privacy, or other rights.

Further Information

(Full details of OUP's publication rights policies, including author rights can be found at https://academic.oup.com/journals/pages/access_purchase/rights_and_permissions/publication_rights)

Author Self-Archiving Policy

On publication of your Article in the Journal you are not required to remove any previously posted ORIGINAL VERSIONS from your own personal website or that of your employer or free public servers of articles in your subject area, provided (1) you include a link (url) to the VERSION OF RECORD on the Journalâ s website; AND (2) the Journal is attributed as the original place of publication with the correct citation details given.

You may post the ACCEPTED MANUSCRIPT of the Article (but not the published version itself) onto your own website, your institutionâ s website and in institutional or subject-based repositories, PROVIDED THAT it is not made publicly available until **12 MONTHS** after the online date of publication, and that: (1) you include a link (url) to the VERSION OF RECORD on the Journalâ s website; (2) the Journal is attributed as the original place of publication with the correct citation details given.

Notes

Author's Original Version: an unrefereed manuscript version of the article, as submitted for review by a journal

Accepted Manuscript: the final draft author manuscript, as accepted for publication by a journal, including modifications based on referees' suggestions but before it has undergone copyediting and proof correction

Free Link to Published Article

On publication of your article, you will receive a URL, giving you access to the published article on the Journal website, and information on use ofthis link.

Educational Use

You may use the Article within your employer's institution or company for educational or research purposes only, including use in course-packs, as long as: (1) you do not use it for commercial purposes or re-distribution outside of the institution/company; (2) you acknowledge the Journal as the original place of publication with the correct citation details given.

brownd32@mcmaster.ca signed this licence on 2018-06-25 16:35:33 GMT.