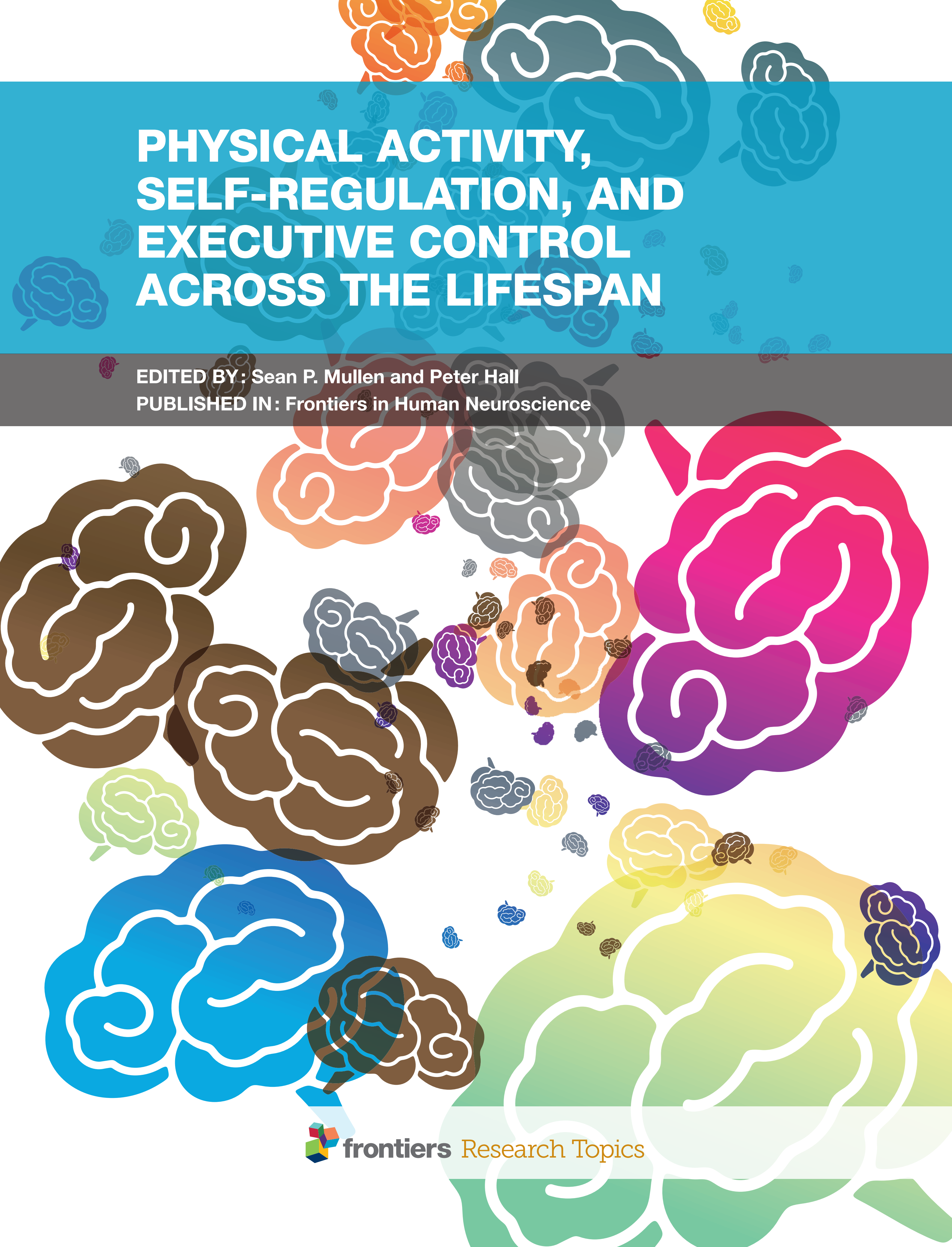

PHYSICAL ACTIVITY, SELF-REGULATION, AND EXECUTIVE CONTROL ACROSS THE LIFESPAN

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PHYSICAL ACTIVITY, SELF-REGULATION, AND EXECUTIVE CONTROL ACROSS THE LIFESPAN

Topic Editors:
Sean P. Mullen, University of Illinois at Urbana-Champaign, USA
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There is overwhelming evidence linking increased physical activity with positive changes in cognitive functioning and brain health. Much of what we know about these interrelationships comes from aerobic exercise training studies with older adults and children. This literature has paved the way for the neuroscientific investigation of mechanisms responsible for exercise-induced cognitive and brain health enhancement, a list that ranges from molecular changes to systemic changes in executive control and neural connectivity. A new perspective has also emerged that aims to understand executive control processes that may underlie the regulation of health behavior. In accordance with this view, physical activity falls under the umbrella of health behaviors that require a substantial amount of executive control.

Executive control is a limited resource, and the aging process depletes this resource. People who regularly exercise are said to have higher “self-regulatory control”—planning, goal-shielding and impulse control—than irregular exercisers. The successful maintenance of physical activity participation in lieu of daily cognitive stressors likely reflects an adaptive resistance to control failures. Indeed, a handful of studies have shown the relationship between greater executive control and subsequently higher levels of physical activity. However, little is known about the neural correlates of physical activity adherence or sedentary behavior, with the view that neurocognitive factors have an antecedent and reciprocal influence on these behaviors. No research has focused on the brain networks responsible for the self-regulation of physical activity, which likely overlaps with structures and functions playing critical roles in the regulation of other health behaviors.

Interdisciplinary investigations are needed to explain the extent to which physical activity self-regulation and self-regulatory failure is dependent upon, or under the influence of executive control processes and brain networks. Understanding the degree to which self-regulatory resources may be enhanced, restored, and trained will have enormous implications for basic science and applied fields. It is also of great import to understand whether or not physical activity self-regulation is a domain-specific behavior associated with specific brain networks, or to determine the extent to which regulatory network-sharing occurs.

The aim of this Frontiers Research Topic is to curate contributions from researchers in social and cognitive neurosciences and related fields, whose work involves the study of physical activity behavior, self-regulation and executive control. For this Research Topic, we, therefore, solicit reviews, original research articles, and opinion papers, which draw theoretical or empirical connections related to sustained physical activity behavior, self-regulatory strategies, cognitive performance, and brain structure and function. While focusing on work in the neurosciences, this Research Topic also welcomes contributions in the form of behavioral studies, psychophysiological investigations, and methodological innovations.

This Frontiers Research Topic will carve out new directions for the fields of exercise, cognitive, and social neurosciences. We hope you will consider submitting your work.

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Table of Contents

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EDITORIAL
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Editorial: Physical activity, self-regulation, and executive control across the lifespan

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Keywords: cognitive control, self-regulation, executive functioning, physical activity, fitness-cognition link, behavioral maintenance, exercise adherence, cardiorespiratory fitness

Physical activity is a complex behavior that involves iterative planning, monitoring, ongoing adjustments, and inhibition of unwanted distractions. These same processes are manifestations of executive control and rely on established neural networks involving the prefrontal cortex (see Buckley et al., 2014). A plethora of evidence exists showing that continued involvement in a physical activity program can enhance multiple domains of executive control. More recently, research has also indicated that executive functioning is associated with the long-term maintenance of physical activity participation. This Research Topic comprises theoretical perspectives (Buckley et al., 2014; Hall and Fong, 2015) and empirical findings (Anderson-Hanley et al., 2014; Best et al., 2014; Blanchfield et al., 2014; Daly et al., 2014; Leckie et al., 2014; Lowe et al., 2014; Moore et al., 2014; Dupuy et al., 2015; Pageaux et al., 2015) underlying the reciprocal relationship between physical activity and executive control.

Although the fitness-cognition link has received a great deal of attention, particularly the effect of cardiorespiratory fitness training on subsequent cognitive performance, there is still much to be learned in children and adults. In a cross-sectional study, Moore et al. (2014) extended this work by showing that children with higher fitness levels performed better on a "large problem" arithmetic task. Moreover, higher fit children showed selective modulation in electrophysiological indices (N170, P3, and N400), suggesting that fitness may augment encoding, attention, and processing during arithmetic tasks. In a similarly designed study of young and older adult women, Dupuy et al. (2015) found that, irrespective of age, fitness was positively associated with Stroop task performance, as well as higher cerebral oxygenation in the right inferior frontal gyrus. In addition to the imaging conducted in the Moore et al. (2014) and Dupuy et al. (2015) studies which offered insight into neurophysiological mechanisms contributing to fitness-enhancing effects on the brain, Leckie et al. (2014) tested a mediational model with brain-derived neurotrophic factor. Specifically, Leckie et al. found that BDNF-1 mediated the effect of a 1-year walking intervention on task-switching performance, but only for those 71 and older. Together, these findings suggest that certain patterns of electrophysiological activity and levels of oxygenated blood in the prefrontal cortex are associated with better fitness levels and executive performance, in children and adults, respectively; whereas physical activity-induced neurotransmitter release may serve to protect brain health among the oldest adults.

It is well-known that one must remain physically active for 6 months or longer to attain a high level of cardiorespiratory fitness. Yet it is also well-understood that many individuals are incapable of sustaining a physical activity program for this long on their own. Rather, successful maintenance of physical typically requires substantial support and supervision. Even then, a high percentage of people drop out from their programs simply due to difficulties negotiating everyday costs of activity participation (e.g., scheduling conflicts, resisting competing sedentary activities).

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From this perspective, although exercise itself may have benefits for the brain centers that support executive control, it may also be the case that strong executive functioning may itself facilitate consistency for this challenging activity. Two studies in this section support this hypothesis. In the first, Daly et al. (2014) tested a bidirectional relationship between physical activity and executive control (defined by verbal fluency and a letter cancellation task), using a prospective design and a large ($n = 4555$) nationally-representative older adult sample. They found poor executive control was associated with lower self-reported physical activity rates over a 2-year period. Moreover, executive control's contribution to physical activity was 50% greater in magnitude than the contribution of physical activity to subsequent changes in executive control. In a second study, examining data from a randomized controlled trial (RCT) with 125 older women, Best et al. (2014) tested the effect of strength training-induced improvements in executive control on subsequent self-reported physical activity during an unsupported, 1-year follow-up period. They found that greater training-induced Stroop gains were associated with better adherence during the unstructured follow-up period.

The effects of aerobic exercise-induced changes in executive control on subsequent maintenance of physical activity may not be entirely straightforward, however. Anderson-Hanley et al. (2014) reported a 6-month follow-up to an RCT involving older adults (40% meeting criteria for mild cognitive impairment), who engaged in 3 months of virtual-reality-enhanced aerobic cycling. Specifically, those with poorer executive control were more likely to engage in self-regulated cycling during the observational period following their supervised program. This inverse relationship was unexpected. The researchers suggested that this population might have been especially committed to counteract their own decline in cognitive functioning. It is also important to note that no other types of physical activity were assessed during the "naturalistic window" and participants may have disengaged from other lifestyle activities such as walking.

For several decades, researchers have also reported evidence of acute effects of exercise on cognitive functioning. Little is known about the direct and indirect spillover effects that exercise and the exercising of one's self-regulatory control may have on other areas of life. Interestingly, Lowe et al. (2014) showed that involvement in a single bout of moderate intensity aerobic activity increased Stroop task performance, and that those with larger effects consumed more non-appetitive foods, possibly representing a compensatory effect. These findings offer preliminary evidence of exercise-induced "transfer effects" to the dietary domain, though many questions still remain about where to look for them.

In two complementary multi-studies (Blanchfield et al., 2014; Pageaux et al., 2015) Marcora and colleagues tested the effects of mental fatigue on submaximal and maximal exercise performance and ratings of perceived exertion (RPE; Pageaux et al., 2015), as well as the effects of subliminally-primed cues, i.e., visual faces and action words, on endurance and RPE (Blanchfield et al., 2014). Contrary to hypotheses, Pageaux et al. (2015) found that participants' maximal exertion was not impacted by a 30-min Stroop task intended to induce central and peripheral fatigue. Performance on submaximal exercise was altered, and this was also associated with higher RPE. Blanchfield et al. (2014) showed that persistence increased and RPE was lower when they primed participants with happy faces (experiment 1) and action words (experiment 2). This series of studies underscore the influence of conscious and subconscious motives on the self-regulation of aerobic training.

Each paper in the topic offers unique insights into the rapidly growing field that we know as exercise neuroscience. Important future directions include examination of activity/brain health relationships in medical populations, and deeper understanding of mechanisms linking brain and behavior in the context of exercise.

AUTHOR CONTRIBUTIONS

Both authors have made substantial contributions to this work at all stages, from the conception and drafting to the final revisions. We have each contributed important intellectual content, approved the final version, and agree to be accountable for all aspects of the work.

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Cognitive control in the self-regulation of physical activity and sedentary behavior

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Cognitive control of physical activity and sedentary behavior is receiving increased attention in the neuroscientific and behavioral medicine literature as a means of better understanding and improving the self-regulation of physical activity. Enhancing individuals' cognitive control capacities may provide a means to increase physical activity and reduce sedentary behavior. First, this paper reviews emerging evidence of the antecedence of cognitive control abilities in successful self-regulation of physical activity, and in precipitating self-regulation failure that predisposes to sedentary behavior. We then highlight the brain networks that may underpin the cognitive control and self-regulation of physical activity, including the default mode network, prefrontal cortical networks and brain regions and pathways associated with reward. We then discuss research on cognitive training interventions that document improved cognitive control and that suggest promise of influencing physical activity regulation. Key cognitive training components likely to be the most effective at improving self-regulation are also highlighted. The review concludes with suggestions for future research.

Keywords: cognitive control, self-regulation, executive functioning, physical activity, sedentary behavior

For nearly half of a century, researchers have been trying to uncover how to motivate people to become more physically active (Trost et al., 2002; Schutzer and Graves, 2004; Buckworth et al., 2013) and, recently, more effort has been made to understand how to motivate people to be less sedentary (Hamilton et al., 2008). Despite resources devoted to these efforts, more than 30% of the world's population remains physically inactive (Hallal et al., 2012) and, on average, people are sitting for more than 300 min/day (Bauman et al., 2011). Our understanding of the regulation of these behaviors has advanced, but these prevalence rates suggest that our knowledge of physical activity and sedentary behavior remains incomplete. Research supports theoretical proposals that health behavior is dependent, in part, on self-regulation capacities (Bandura, 1986; De Ridder and de Wit, 2006), but only recently has research attention been directed toward the preceding factors of self-regulation that influence physical activity and sedentary behavior.

Recent theory (e.g., Temporal Self-Regulation Theory; Hall and Fong, 2007, 2010, 2013) and evidence suggest that the relation between physical activity and cognitive control is reciprocal (Daly et al., 2013). Most research has focused on the beneficial effects of regular physical activity on executive functions-the set of neural processes that define cognitive control. Considerable evidence shows that regular physical activity is associated with enhanced cognitive functions, including attention, processing speed, task switching, inhibition of prepotent responses and declarative memory (for reviews see Colcombe and Kramer, 2003; Smith et al., 2010; Guiney and Machado, 2013; McAuley et al., 2013). Recent research demonstrates a dose-response relationship between fitness and spatial memory (Erickson et al., 2011), however the long-term effects of physical activity on working memory have been less consistent (Smith et al., 2010).

Positive physical activity effects on executive function have been found in children for both acute and regular activity (Chang et al., 2012; Hillman et al., in press). For example, findings from a 9-month randomized controlled trial in 221 prepubertal children attending an afterschool physical activity program (vs. a wait-list control group), showed improvements in fitness (VO_{2peak}), cognitive control, and neuroelectrical activity (P3-ERP) during tasks that required significantly more cognitive control (Hillman et al., in press). In addition, a modest dose-response effect of program attendance on cognitive control measures was also found. Improvements in cognitive function are not always observed in older adults (Angevaren et al., 2008) or in children (Janssen et al., 2014) involved in physical activity programs. These findings suggest that the effects of physical activity on cognitive function may depend on the particular cognitive function being assessed. Taken together, this research suggests that physical activity training can enhance cognitive control abilities. The effects of physical activity on cognitive control appear to be underpinned by a variety of brain processes including: increased hippocampal volume, increased gray matter density in the prefrontal cortex (PFC), upregulation of neurotrophins and greater microvascular density (for a review see Voss et al., 2013). Much less is understood about the influence of cognitive control on physical activity but emerging evidence suggests that executive functions play an antecedent role in effective self-regulation of physical activity (Hall et al., 2008; Riggs et al., 2010; McAuley et al., 2011; Daly et al., 2013; Pentz and Riggs, 2013; Best et al., 2014).

The goals of this paper are (1) to review emerging evidence of the antecedence of cognitive control abilities in enabling successful self-regulation for physical activity, and in precipitating self-regulation failures that predispose individuals to remain sedentary; (2) to highlight neural networks that may underlie the cognitive control of physical activity and sedentary behavior; and (3) to review emerging research on training effects on cognitive and physical functioning and summarize components of training that may produce positive cognitive outcomes associated with increased physical activity engagement.

SELF-REGULATION, PHYSICAL ACTIVITY AND SEDENTARY BEHAVIOR

Health behavior is determined from the interplay between personal influences, behavior and environmental factors (Bandura, 2004). Although external circumstances play an important role in facilitating or impeding physical activity (for reviews see French et al., 2001; Trost et al., 2002) and sedentary behavior (Owen et al., 2010), to a large degree, external factors influence behavior through the mediation of a person's cognitive processes (Bandura, 2001). Executive functions, in particular, are pivotal to cognitive control. Executive function is an umbrella term encapsulating a variety of higher-order cognitive processes that regulate, control, and modulate information from many cortical-subcortical brain regions to support goal-directed behavior (Blair and Ursache, 2011; Otero and Barker, 2014). Executive functions and the capacity to symbolize enable individuals to self-regulate by internal representations regarding future goal-directed actions (Bandura, 2001; Barkley, 2001). From this perspective, internal representations of future consequences allow people to exert adaptive control anticipatorily over their behavior and thereby manipulate, alter, and influence their environments. Rapid technological and societal evolution has reduced the function of physical activity as a requisite and inherent part of everyday life (Conroy et al., 2010). These changes have increased the importance of cognitive control capacities for the self-regulation of physical activity for health in contemporary society. Self-regulatory systems operate through goals, beliefs, self-monitoring, evaluative self-reactions, and self-regulatory processes (Bandura, 1986, 1997; Suchy, 2009; Hagger, 2010; Hall and Fong, 2010). Self-regulation implies the modulation of thought, affect, behavior, or attention via deliberate or automated use of cognitive control mechanisms (Karoly, 1993). Given the intrinsic plasticity of the cognitive control system (Anguera et al., 2013) it is possible that advanced cognitive control capacities are underpinned by brain networks specialized for self-regulation.

Short- and long-term self-regulation success can be enhanced with control over limited executive attentional resources (Sethi et al., 2000; Rueda et al., 2005). Attention biases seem to differ as a function of physical activity (Hawkins et al., 1992; Kramer et al., 1999a). For instance, physically active people have stronger cognitive and evaluative biases toward physical activity-related concepts than less physically active individuals (Calitri et al., 2009; Conroy et al., 2010; Hyde et al., 2010; Berry et al., 2011). Strong evaluative biases have been prospectively associated with objectively measured physical activity behavior (Conroy et al., 2010). Also, experienced exercise self-regulators display non-conscious biases towards exercise self-regulatory processes (Buckley and Cameron, 2011a), and towards associating exercise self-regulatory concepts (e.g., self-efficacy) as self-relevant compared to those with less experience (Buckley and Cameron, 2011b). In contrast, less experienced exercise self-regulators appear biased towards associating exercise disengagement as self-relevant, and sedentary individuals, display negative biases toward physical activity (Bluemke et al., 2010). Together, this research suggests that an improvement in control processes, such as attention and inhibition or interference control, is associated with an improvement in self-regulation of physical activity.

COGNITIVE CONTROL AND SELF-REGULATION OF PHYSICAL ACTIVITY

Self-regulation capacity is intricately linked to executive functions (Hofmann et al., 2012). Core executive functions include updating and monitoring of relevant information in working memory, inhibitory control, including self-control (behavioral inhibition) and interference control (selective attention and cognitive inhibition), planning, scheduling, and flexible switching between different tasks or mental sets (set-shifting; cognitive flexibility; for reviews see Miyake et al., 2000; Lehto et al., 2003; Diamond, 2013). These functions afford the cognitive control that enable individuals to maintain goals across prolonged periods of time, flexibly adapt behavior to changing demands and detect conflict and discrepancy and adjust behavioral control accordingly (Botvinick et al., 2001; Braver and Barch, 2006). Cognitive control abilities, therefore, partly underlie the capacity for self-regulation.

People with greater self-regulation capacity engage in more healthful behaviors and are more successful at implementing their intentions to be physically active (de Bruin et al., 2012). Efficient executive functions support self-regulatory mechanisms that underpin successful goal pursuit (Hofmann et al., 2012). For instance, people with high working memory capacity are more adept at sustaining attention on a focal task (e.g., Engle, 2002) and are better able to resist attentional capture by distracting stimuli at early stages of self-regulation processing (Friese et al., 2010), have greater ability to inhibit intrusive thoughts (Brewin and Beaton, 2002) and are more successful at downregulating unwanted "hot" processes such as, negative affect and cravings (Gyurak et al., 2012). Moreover, people that are effective at inhibiting habitual, prepotent responses are more successful at suppressing, ignoring or disengaging from distracting information that might interfere with their self-regulatory efforts (Hofmann et al., 2008).

Increasingly, the primacy of cognitive control abilities in physical activity behavior is receiving strong empirical support (e.g., Hall et al., 2006; Riggs et al., 2010; McAuley et al., 2011; Daly et al., 2013; Pentz and Riggs, 2013). Of particular note, Hall et al. (2008) demonstrated that individual differences in executive function uniquely predict physical activity behavior.

Specifically, greater baseline levels of inhibition control, as indicated by better performance on a reaction time measure of executive function (Go/NoGo task) was associated with physical activity over a subsequent 7-day period. McAuley et al. (2011) examined the relationship of executive function, self-regulation and self-efficacy in adherence to a 12-month exercise intervention for older adults. McAuley et al. found that at the start of the exercise program, higher levels of executive ability to coordinate tasks and inhibit habitual responses together with greater use of self-regulatory strategies were associated with higher levels of exercise self-efficacy. In turn, higher self-efficacy was linked to better adherence to weekly physical activity during the ensuing 11 months. Together, this research suggests that at the start of an exercise program, stronger cognitive control abilities are directly and indirectly associated with increased physical activity behavior. Furthermore, in a multi-wave longitudinal study investigating the reciprocal relationship between executive function and physical activity in 4555 older adults (Daly et al., 2013), it was found that changes in executive function corresponded with changes in physical activity. High levels of executive function predicted a longitudinal increase in physical activity. However, older adults with poor executive function tended to show large decreases in their rates of participation in physical activity over time. The magnitude of the relationship between physical activity and cognitive performance was shown to be strongest in the direction from executive function to physical activity. These findings suggest that with increasing age, executive function plays a predictive role in physical activity participation. Similarly, findings from research examining the relationship between executive function and physical activity in children show that poor performance on executive function tasks prospectively predict low levels of physical activity (Riggs et al., 2010; Pentz and Riggs, 2013).

COGNITIVE CONTROL AND SEDENTARY BEHAVIOR

When self-regulation capacities are limited, i.e., fatigued, underdeveloped or disengaged, health behaviors are more strongly influenced by subtle, transient behavioral prepotency effects and temptations (Hall and Fong, 2007; Pontus Leander et al., 2009). Without efficient cognitive control abilities, people are more likely to give in to temptations when exposed to them and are predisposed to undermine their self-regulatory functioning. Limited self-regulatory capacity is associated with overeating, smoking, drug use, unsafe sex and low adherence to physical activity (Ayduk et al., 2000; Tarter et al., 2003; Bogg and Roberts, 2004; Nigg et al., 2006; Hagger, 2010). Relatively lower cognitive control increases the likelihood that individual (e.g., bad mood) and situational (e.g., cognitive load) risk factors will contribute to self-regulatory failures (Hofmann et al., 2012). For example, individuals with low working memory capacity have greater difficulty overcoming attentional biases (Friese et al., 2010) and are less able to resist attending to distractors (Unsworth et al., 2004), are more vulnerable to intrusive thoughts (Brewin and Smart, 2005) and unintended mind wandering (Kane et al., 2007). People with relatively lower cognitive control are also less able to disengage from affective reactions towards temptations (Hofmann et al., 2008) and find it difficult to inhibit or override impulsive behavior responses (Hofmann et al., 2009).

In daily life, people often pursue physical activity goals in the face of multiple alternative goals (e.g., work goals) and temptations that compete for limited cognitive resources. These goal conflicts and temptations can impose a self-regulation dilemma (Fishbach and Zhang, 2008). Recent evidence suggests that executive functions may play a causal role in resolving competing health behavior influences (Hall and Marteau, 2014). Cognitive control abilities, such as effective working memory operations, allow people to proactively maintain accessibility of physical activity goals and reactively resolve competition by inhibiting competing interests, thereby reducing the risk that they will give in to sedentary temptations and predispositions.

Sedentary behavior is a distinct construct from physical activity and has independent and qualitatively different effects on health and physical function (Hamilton et al., 2008; Katzmarzyk et al., 2009; Tremblay et al., 2010). Sedentary behavior is defined as any waking behavior characterized by a low energy expenditure of less than or equal to 1.5 metabolic equivalents (METs) while in a sitting or reclining posture (Tremblay et al., 2012; Sedentary Behavior Research Network, 2014). Sedentary behavior can be categorized into transformational (e.g., driving), occupational (e.g., using a computer), and/or leisure (e.g., watching TV; Voss et al., 2014). Research suggests that chronic, unbroken periods of muscular unloading associated with prolonged sedentary time is linked with increased all-cause mortality and risk of chronic diseases (Hamilton et al., 2007, 2008), and with deleterious health outcomes associated with cognition and brain health (Voss et al., 2014). Prolonged sitting has been shown to be associated with increased premature death risk after controling for factors such as age, smoking status, gender, education, body mass index and living in urban or city environments (van der Ploeg et al., 2012). Interruptions to sitting time have been shown to have metabolic-health benefits (Dunstan et al., 2011). Much less is understood about the regulatory determinants of sedentary behavior, and very few studies have explicitly examined the relationship between executive function and sedentary behavior. Nonetheless, there is preliminary evidence that lower executive function is directly and indirectly associated with sedentary behavior. For example, Hoang et al. (2013) found that young adults who initially exhibited low levels of physical activity and remained relatively inactive for 25 years had nearly twofold greater odds of impaired executive function compared with those who exhibited higher activity levels; very-low physical activity patterns were associated with even more pronounced declines in executive functioning. Similarly, in older adults, sedentary behavior indirectly led to poor executive function through depressive symptoms (Vance et al., 2005). Sedentary individuals have also been shown to have inefficient task switching abilities as indicated by greater switch costs compared to those that are more active (Hawkes et al., 2013). That is, sedentary individuals display less capacity to quickly and accurately switch between tasks. In a study of 9–10 year-old children, executive control proficiency was negatively associated with sedentary behavior possibly reflecting a lack of cognitive capacity to plan exercise and/or to regulate urges to remain sedentary (Riggs et al., 2012).

In addition to keeping goals in mind and inhibiting habitual, unhealthy responses, effective self-regulation requires cognitive flexibility, i.e., the ability to shift between multiple tasks or mental sets (Monsell, 2003). Prior research has established that in switching from one task to another, the two executive control processes of goal shifting and rule activation each take time (Rubinstein et al., 2001). Smaller switching costs reflect more efficient executive functioning (Monsell, 2003). Although the connection between task switching and self-regulation has received less attention, findings from a randomized controlled trial in older adults, demonstrated that task switching abilities improved with concurrent increases in cardiorespiratory fitness (Kramer et al., 1999b). The extent to which task-switching promotes or impedes self-regulation is a function of task context and motivational factors (Hofmann et al., 2012). Given that mental set—an individuals' tendency to repeatedly approach a situation in the same way—is a precursor to habit (Galarce and Kawachi, 2013), the ability to change perspectives or to rapidly adjust strategies in line with changing demands or priorities is likely a prerequisite for engaging in regular physical activity. Together, the discussed research suggests that executive control abilities affect the emergence as well as the regulation of physical activity and sedentary behavior. Furthermore, in line with recent neuroscience models (e.g., Power et al., 2011), self-regulation of physical activity and sedentary behavior is likely implemented via dynamic and flexible "control" neural networks.

NEURAL NETWORKS OF COGNITIVE CONTROL AND SELF-REGULATION

Recent advances in neuroscience research demonstrate that cognitive control emerges from multiple, distinct, functional brain networks that flexibly interact in the service of goal directed action (Bressler, 1995; Goldman-Rakic, 1995; McIntosh, 2000; Mesulam, 2005; Fuster, 2006; Fair et al., 2009; Bressler and Menon, 2010). Within broadly distributed networks, dynamic functional connectivity between brain regions specialized to support self-reflection, cognitive control and those associated with the salience, reward and emotional value of a stimulus provide the neural underpinnings of goal-directed behavior (Fuster, 2001; Pochon et al., 2002; Aron et al., 2004; Banfield et al., 2004; Vincent et al., 2008; Menon and Uddin, 2010; Spreng et al., 2010; Heatherton and Wagner, 2011).

Making a decision to engage in physically active or sedentary behaviors likely activates a variety of brain regions that continuously compete to determine the direction of a person's thoughts and behavior. Indeed, evidence suggests that competing brain regions are activated in decisions involving the physical and mental effort cost associated with an action (Botvinick et al., 2009). Activity in prefrontal regions associated with cognitive control (e.g., the dorsal anterior cingulate cortex (dACC)) and subcortical regions associated with reward (e.g., amygdala, ventral striatum, mesolimbic dopamine pathway) have been shown to vary when people make decisions about whether an action is worth taking relative to the physical and mental effort they are required to invest (Walton et al., 2003, 2006; Kurniawan et al., 2010). Cognitive control mechanisms are crucial for "biasing" neural competition in favor of goal-directedness (Miller and Cohen, 2001; Blair and Ursache, 2011; Hanif et al., 2012). By amplifying activity in neural structures responsible for processing goal-relevant information and attenuating/suppressing competing neural activity, executive functions direct attention selectively towards self-regulatory cues, making them more likely to guide behavior.

To our knowledge, no research has focused on the brain networks responsible for the self-regulation of physical activity. Nonetheless, choosing to engage in physical activity requires the capacities to engage internally focused thoughts about physical activity as well as make decisions based on long term rewards, disengage from cues associated with more immediate outcomes and override long standing, but interfering habits. Thus, the self-regulation of physical activity likely shares conceptual similarities with other domains of intertemporal choice that depend upon the integration of cognitive control abilities (e.g., healthy eating, smoking cessation). Cognitive control mechanisms have been increasingly implicated in the self-regulation of a wide range of health behaviors (Insel et al., 2006; Nes et al., 2009; Williams et al., 2009; Hall, 2012; Jasinska et al., 2012), and emerging literature shows that baseline levels of these abilities improve with training (Olesen et al., 2004; Erickson et al., 2007; Dahlin et al., 2008). This research implies that multiple types of self-regulation may engage overlapping neural networks (Aron et al., 2004; Cohen and Lieberman, 2010; Cohen et al., 2013). Evidence that PFC regions are consistently recruited in exerting control across different self-regulation domains, but subcortical regions of this top down control are dependent on the nature of the stimulus and the regulatory context offers support for this idea (Cohen and Lieberman, 2010; Heatherton and Wagner, 2011). Self-regulation therefore, requires a balance between prefrontal and subcortical brain networks.

Building on these neuroscience developments, it is plausible that the self-regulation of physical activity and sedentary behavior is implemented via overlapping networks of brain regions (see **Figure 1**) including (1) the default mode network (DMN) involved in resting states and internal thought (Andrews-Hanna, 2012); (2) PFC regions involved in cognitive control—particularly, the "fronto-parietal" network implicated in initiation and flexible adjustments in control and the "cingulo-opercular" network implicated in prolonged maintenance of task context (Dosenbach et al., 2007, 2008); and (3) brain regions and pathways associated with reward (e.g., ventromedial prefrontal cortex (vmPFC), amygdala, ventral and dorsal striatum, mesocortical and mesolimbic) (McClure et al., 2004; Draganski et al., 2008; Van Leijenhorst et al., 2010).

SELF-REFLECTION AND PHYSICAL ACTIVITY

In contemplating physical activity, people often engage in introspection on their aspirations for exercise, planning exercise sessions, and evaluating exercise goals and discrepancies. During these periods of self-reflection, the DMN, a set of interconnected brain regions including the medial prefrontal cortex (mPFC) and posterior cingulate cortex (PCC), the retrosplenial cortex (RSC), the medial and lateral temporal lobes, and the posterior inferior parietal lobes (pIPL) is engaged (Northoff et al., 2006; Buckner et al., 2008; Stawarczyk et al., 2011; Moran et al., 2013). Although activity in the DMN has been most often associated with resting states, recent research has implicated activity in

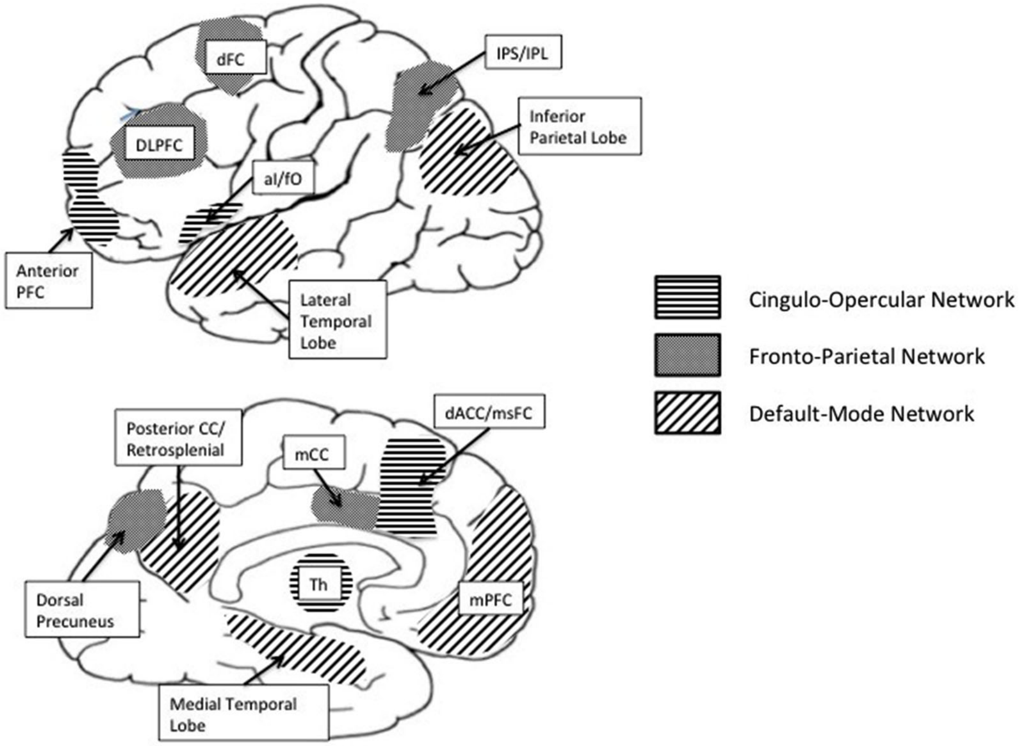

FIGURE 1 | Brain networks associated with cognitive control.

the DMN with simulations of internal experience including mind wandering and the recollection of personal preferences, beliefs, feelings and abilities (Ochsner et al., 2004; Amodio and Frith, 2006; van Overwalle, 2009; Andrews-Hanna, 2012). Mind wandering can promote or impede goal directed behavior (Smallwood and Andrews-Hanna, 2013). For instance, mind wandering is associated with adaptive self-regulatory skills such as, planning, problem solving and delay of gratification (Schacter et al., 2007; Suddendorf and Corballis, 2007; Suddendorf et al., 2009), and with a style of decision-making characterized by patience rather than impulsivity (Smallwood et al., 2013). These regulatory processes enable people to select optimal courses of action to achieve their goals. Mind wandering can also manifest as self-regulation failures in situations where people experience goal neglect. In such situations, unintended lapses of attention have been shown to lead people to automatically engage well-established habits instead of acting in accordance with current goals (McVay and Kane, 2009, 2010). Given the association of mind wandering with self-regulatory success and failure, it seems plausible that in physically active individuals, mind wandering may be linked to thoughts about planning or overcoming physical activity barriers that aid self-regulatory efforts whereas, in individuals that remain sedentary, mind wandering may trigger thoughts that lead them to neglect their physical activity goals.

Research on the relationship between the DMN and executive function demonstrates that increased activity in the DMN is associated with increased memory capacity in young adults (Hampson et al., 2006) and improved performance on a variety of tasks that assess cognitive control in older adults (Persson et al., 2007; Voss et al., 2010). Voss et al. reported that increased functional connectivity within the DMN, and between the DMN and a frontal executive network, is associated with aerobic fitness and with activities that appear to engage executive functions required for learning exercise routines. The DMN shows reduced activity during cognitive tasks that require externally focused goal-directed attention (Fox et al., 2005; Fox and Raichle, 2007).

TRANSLATING MENTALLY REPRESENTED GOALS TO BEHAVIOR

Translating internally represented physical activity-related goals to action requires people to keep goals in mind, direct attention away from distractors, inhibit competing impulses and make decisions about how to proceed. These cognitive processes are subcomponents of executive functions and are associated with increased activity in prefrontal brain networks that exert a supervisory function that governs the regulation of behavior (Bickel et al., 2012). Regulation of physical activity behavior likely requires cognitive control optimized for both rapid adaptive control via the fronto-parietal network and for sustained goal-oriented cognitive control via the cingulo-opercular network (Dosenbach et al., 2007; Draganski et al., 2008).

Brain regions associated with the “fronto-parietal” network include the dorsolateral prefrontal cortex (dlPFC), the inferior parietal cortex (IPC), the dorsal precuneus (DPC), precuneus and middle cingulate cortex (mCC; Dosenbach et al., 2007). The dlPFC is a key region in the "fronto-parietal" network and is implicated in the integration, maintenance and manipulation of goal relevant information in working memory (Fuster and Alexander, 1971; Barbey et al., 2013). Anterior aspects of the dlPFC are involved in attentional switching, selective attention and sustained attention (D'Esposito and Postle, 1999; MacDonald et al., 2000). As such, the dlPFC has been found to be associated with self-regulatory capacities such as planning, selection and initiation of action and the ability to flexibly adjust mental set (Alvarez and Emory, 2006; Clark et al., 2008). In the context of health behaviors, evidence suggests that activity in the dlPFC is associated with "on-line" processing of information linked to health behavior choices (Hare et al., 2011), and with successful self-regulatory control (Harris et al., 2013). The initiation and flexible adjustments in control associated with the "fronto-parietal" network is complemented by activity in the cingulo-opercular network hypothesized to be involved in sustained task maintenance during cognitive control (Dosenbach et al., 2007).

Sustained goal oriented control is implemented by the set of interconnected brain regions that make up the cingulo-opercular network including the anterior prefrontal cortex (aPFC), the anterior ventrolateral prefrontal cortex (aVPC), and the dorsal anterior cingulate/medial superior frontal cortex (dACC/msFC). The aPFC is a key region in the cingulo-opercular network and is involved in the integration of working memory with the allocation of attentional resources in the pursuit of higher order behavioral goals (Ramnani and Owen, 2004). Activity in the aPFC is associated with the ability to keep in mind over time a high level goal while performing associated subgoals (Koechlin and Hyafil, 2007), an important regulatory process in the pursuit of physical activity goals. It is therefore likely that activity in the aPFC will be associated with physical activity and sedentary behavior.

Another key region in the cingulo-opercular network is the ventrolateral prefrontal cortex (VLPFC). Activity in the VLPFC has been implicated in cognitive control of memory (Badre and Wagner, 2007) and in response selection and inhibition (Aron et al., 2004; Badre and Wagner, 2004). The left anterior VLPFC has been associated with the retrieval of relevant knowledge from memory (Badre and Wagner, 2007). The right VLPFC plays a central role in exerting both intentional and incidental self-control across multiple domains, particularly in conflict situations between goal-directed intentions and a prepotent impulse (Cohen et al., 2013). Activity in the right VLPFC is associated with the ability to inhibit habitual responses to cues or to inhibit a previously rewarded response in order to be able to make a different one (Cohen et al., 2013). Greater activity in the right VLPFC is associated with choosing delayed goal-related options (Monterosso et al., 2007). Regularly active individuals—those that complete at least 30 min of activity five times per week, or 20 min of vigorous activity three times per week—are likely characterized by exercise decisions that preferentially favor distal benefits (e.g., health benefits). Sedentary individuals may be distinguished by work and/ or leisure priorities that involve prolonged sitting or by the tendency to indulge immediately available passive rewards (e.g., relaxation, comfort). To some degree, it is likely that engaging in regular physical activity is associated with activity in the VLPFC. Moreover, given that the right VLPFC is activated in situations where people have to inhibit a previously rewarded response in order to be able to make a different one, it is possible that endeavors to change sedentary behavior may also be associated with activity in the right VLPFC.

In sum, the cingulo-opercular and the fronto-parietal networks work together to support executive functions that enable flexible and stable cognitive control of goal-directed behavior (Dosenbach et al., 2007). Additionally, engaging in goal pursuit activates several representational processes simultaneously, some of which might conflict, and only one of which can be expressed behaviorally at any time (Berkman and Lieberman, 2009). Thus, a control mechanism is required for signaling discrepancy between a current state and desired end-state, and in situations when processes produce conflicting responses.

COGNITIVE CONTROL OF GOAL CONFLICTS

The anterior cingulate cortex (ACC) is a primary cortical area implicated in situations of conflict among multiple representations of response options or among actual response behaviors (Carter et al., 2000; Botvinick et al., 2001; Paus, 2001). The ACC is interconnected with cortical and subcortical (limbic-amygdala) brain regions and is active in the modulation of cognitive (dACC) and emotional (vACC) processing (Bush et al., 2000). The ACC evaluates and monitors for conflict and errors that signal the need to adjust control, particularly when a response requires selection among conflicting alternatives or when incongruity exists between intended and actual response (Bush et al., 2000; Botvinick et al., 2001, 2004; Holroyd and Coles, 2002). The ACC has dense connections with lateral frontal and parietal structures such that, in situations of conflict the ACC recruits the dlPFC to resolve conflicts and guide behavior (Kerns et al., 2004). The links between the ACC and the thalamus and brain stem nuclei implicate the ACC in arousal and drive states, and projections from the ACC to the motor cortex and the spinal cord implicate the ACC in aspects of motor control (Paus, 2001). The functional overlap of ACC connected domains implicates the ACC in both the initiation of action and in overriding competing alternatives (Paus, 2001). Thus, executive functions required to translate intention into action are supported by the ACC.

In the context of physical activity, Hall et al. (2008) used a Stroop task, a measure of response inhibition, wherein incongruent color–word pairs only were presented, and functional imaging to examine the role of ACC in individuals successful and unsuccessful at consistently translating their physical activity intentions into action. They found that unsuccessful self-regulators, i.e., those who were characterized by low intention-behavior consistency, demonstrated a significantly higher degree of activation in the ACC when performing the incongruent Stroop task relative to successful self-regulators, i.e., individuals characterized by high intention-behavior consistency. These findings suggest that, unsuccessful self-regulators, display greater recruitment of cognitive resources in the ACC, as indicated by increased activation of error detection and deliberative processes in response to the cognitive challenge posed by the Stroop task. However, the ACC is seldom activated in isolation of other regions involved in self-regulatory control, such as the orbitofrontal cortex (OFC; Walton et al., 2007). The OFC is functionally connected to prefrontal (dlPFC, ventrolateral PFC) and subcortical (e.g., basal ganglia, amygdala) regions, and this connectivity enables the OFC to act as an interface between affective information and symbolic processing associated with prefrontal regions. The OFC appears to be involved in evaluating the motivational or emotional significance of incoming information (Krawczyk, 2002; Ramnani and Owen, 2004), and is activated when people make long-term decisions (Wallis, 2007), as well as when they attend to consequences of actions (Walton et al., 2007).

AN INTEGRATED SYSTEM OF SELF-REGULATION

The cognitive-control networks and the DMN operate as a functional system in the control of external and internal attention (Vincent et al., 2008; Gerlach et al., 2011). It appears that a key role of the DMN is to dynamically link self-reflection with goal-directed activities through interacting neurocognitive networks (Treserras et al., 2009; Vann et al., 2009; Voss et al., 2010). Within these networks, the right anterior insula has been shown to play a key role in switching between the DMN and cognitive-control networks (Menon and Uddin, 2010). Increased connectivity at rest between the right insula and elements of the cognitive-control network has been shown to support more efficient switching between the DMN and control networks (Hasenkamp and Barsalou, 2012; Tang et al., 2012). Efficient co-activation and/or switching between these brain states is crucial for self-regulation. Given evidence that individual differences in regulatory activity between the default mode and cognitive-control network is associated with variability in goal-directed behavior (Kelly et al., 2008), it is quite possible, that to some degree, physical activity and sedentary behavior may emerge from differences in these interconnected networks. Differences in the nature and strength of brain activation during self-regulatory tasks and differences in the level of connectivity between the DMN and the cognitive-control network may underpin self-regulatory processes that influence physical activity and sedentary behaviors.

COGNITIVE CONTROL AND REWARD PROCESSING IN HEALTH DECISIONS

People often evaluate the rewarding properties (value) of a behavior when making decisions about whether to engage in it. The ability to anticipate the reward value of physical activity and then use that information to develop and execute an action plan efficiently is likely to partially underlie physical activity behavior. This idea is supported by research suggesting that in contexts individuals consider rewarding, cognitive control can be increased (Pochon et al., 2002; Locke and Braver, 2008). In these contexts, increased activity in the dlPFC guides anticipatory implementation of behavioral goals within working memory (Jimura et al., 2010) and increased activity in the frontopolar PFC is associated with maintaining an overall goal while simultaneously performing tasks linked to related subgoals (Koechlin et al., 1999; Braver and Bongiolatti, 2002). For individuals who consider physical activity a rewarding behavior, increased recruitment of brain regions that support cognitive control may enable them to sustain attention on their long-term exercise goals, experience fewer lapses in control and exert more effort to maximize the health benefits attained from physical activity.

The health benefits of physical activity accrue over the long term, thus making decisions regarding physical activity and sedentary behavior requires a balance between reward-seeking and inhibitory control processes. Cognitive control processes are instrumental in determining whether individuals make healthy choices. Cognitive control prefrontal regions are densely interconnected with brain regions and pathways associated with reward (vmPFC, amygdala, ventral and dorsal striatum, mesocortical and mesolimbic). Differential contributions of the PFC and subcortical networks underlie self-regulation success and failure (Bruce et al., 2011; Heatherton and Wagner, 2011). Indeed, effective connectivity between prefrontal and subcortical regions associated with intertemporal choice has been shown to predict individual differences in the self-control of health behaviors (Hare et al., 2014). Successful self-regulation occurs to the extent that the prefrontal-subcortical balance favors control-related PFC regions that support goal-directed action over competing subcortical activity linked to impetuous behaviors. Shifting the balance from activity in prefrontal regions to subcortical limbic structures, either due to habitual cue reactivity, or impaired prefrontal function (e.g., relatively lower cognitive control ability, negative mood) precipitates self-regulation failure (Heatherton and Wagner, 2011).

Cognitive regulation occurs through two mechanisms; value modulation in which the value (reward) assigned to a stimulus is changed and behavioral control in which the weight given to the assigned value during the action selection process is changed (Hutcherson et al., 2012). Neuroimaging research suggests that the vmPFC, the dlPFC and the inferior frontal gyrus (IFG) operate as a valuation circuit (Aron et al., 2004; Hare et al., 2009; Jasinska et al., 2011). The vmPFC is involved in computing the subjective value of a goal and in using this value to bias subsequent behavioral choice (Rangel and Hare, 2010; Jasinska et al., 2011). The dlPFC is involved in modulating the vmPFC so that its activity takes into account the value of long-term, abstract goals (e.g., be healthy; Hare et al., 2014). The IFG is implicated in interference resolution and response inhibition (Aron et al., 2004).

Recent findings from a series of studies on healthy food choices by Hare et al. (2011); Harris et al. (2013) and Hare et al. (2014), showed that modulation of the vmPFC by the dlPFC is critical in making decisions that are consistent with long-term health goals. For example, Hare et al. showed that immediately rewarding aspects of food (e.g., tastiness) are preferentially incorporated into values computed by the vmPFC, whereas more abstract values (e.g., healthiness) are only represented strongly if the dlPFC comes online and modulates activity in vmPFC so that it weights all attributes according to high level goals (e.g., make healthier choices). Additionally, they found that although the vmPFC encoded the value of food attributes at the time of choice for both successful and unsuccessful self-regulators, a pattern of increased effective connectivity between the dlPFC and the vmPFC was exhibited only for individuals successful at exerting dietary self-control. In successful self-regulators, increased activity in the dlPFC likely reflects the engagement of executive functions such as, inhibiting or attenuating hedonic stimulus attributes and allocating more attention to long-term health goals, thus enabling these individuals to choose delayed rewards. The extent to which people are able to exert cognitive control to prioritize the long term value of physical activity over immediate rewards is likely associated with physical activity behavior. It is possible that differences in the efficiency of functional connectivity of the dlPFC–IFG–vmPFC network may be associated with physical activity levels.

A key source of self-regulation failure may be the tendency of the valuation circuit to disproportionately weigh immediate rewards as more valuable comparative to delayed future rewards (McClure et al., 2004; Mitchell et al., 2011). Without sufficient activity in prefrontal cognitive control regions to modulate activity in reward circuits the balance of neural activity may shift from prefrontal to subcortical reward systems, such as the mesolimbic dopamine system- associated with choosing immediate rewards and impulsive behavior (Heatherton and Wagner, 2011). Subcortical reward systems can carry opposing sources of information from those originating in the PFC (Miller and Cohen, 2001; Heatherton and Wagner, 2011). Sedentary behavior may be partially a reflection of self-regulation failure resulting from an increased sensitivity to the rewarding effects associated with sitting and inactivity-related cues (e.g., TV, computer, and elevator) and compromised cognitive control ability to exert strategic attention or inhibit impulses in the presence of such cues.

In sum, the aforementioned research suggests that effective modulation of activity in subcortical reward regions by prefrontal networks that support cognitive control is central to making decisions that are consistent with long term health goals. In line with accumulating evidence of training induced cognitive and neural plasticity (Karbach and Schubert, 2013), training executive control abilities may enhance cognitive control processes to better modulate and bias the value of physical activity in line with long-term benefits.

NEUROPLASTICITY AND TRAINING FOR TRANSFER

The reciprocal relationship between cognitive control and physical activity implies that exercise and/or cognitive training may elicit mutually beneficial outcomes. Both aerobic and resistance training programs (Kramer et al., 1999a; Colcombe and Kramer, 2003; Liu-Ambrose et al., 2010a,b; Erickson et al., 2011) have been shown to be effective at improving cognitive control across the lifespan. This work suggests that significant training-induced cognitive plasticity can occur during aging. Combined physical activity and cognitive training interventions, either sequentially or simultaneously, has also been shown to lead to improvements in cognitive control in adults with and without cognitive impairment (Lawla et al., 2014).

Recent research has demonstrated the antecedent role of cognitive control in the self-regulation of physical activity (Best et al., 2014). This work builds on prior evidence linking greater cognitive control to subsequent higher levels of physical activity (Hall et al., 2008; McAuley et al., 2011). Specifically, Best et al. (2014) found that older women who were involved in exercise training, and who also improved their executive function, subsequently maintained higher levels of physical activity over a following 12-month period.

Increasingly, research shows that cognitive control abilities are malleable, and that cognitive training can produce positive cognitive outcomes and improvements in daily function (Willis et al., 2006; Hertzog et al., 2008) that can have long-lasting effects (Rebok et al., 2014). Approaches to cognitive training are numerous and varied; however, the relative superiority of different approaches with regard to training and transfer continue to be debated. One avenue that is garnering empirical evidence for augmenting cognitive control of physical activity is computerized training of cognitive control abilities. Research suggests that computerized training provides an effective and less labor-intensive approach for enhancing executive functions (Kramer et al., 1999b; Kueider et al., 2012). Findings from computerized cognitive training interventions show that, among older healthy older adults, mind-body aerobic exergaming (Anderson-Hanley et al., 2012), dance-step video games (Schoene et al., 2013), exergaming with a dual-task component (e.g., Microsoft Kinect-controlled Sudoku; Kayama et al., 2014), and stationary computer-based dual-task paradigms lead to modest improvements in cognitive functioning as well as positive transfer effects on balance and gait speed (Li et al., 2010; Verghese et al., 2010).

Recent research suggests that cognitive training efforts may be more effective if they contain key components such as feedback, adaptive progression, multitasking and training sessions spaced over time, that are specifically tailored to the domain of interest (Anguera et al., 2013; Mishra and Gazzaley, 2014; Wang et al., 2014). Moreover, evidence suggests that uni-modal interventions (i.e., focusing on one aspect of functioning) are more effective at generating improvements in individual cognitive abilities whereas multi-modal interventions may show greater transfer effects (Cheng et al., 2012). Understanding the components of cognitive training programs with the most potential to generate positive cognitive outcomes and improve transfer effects to real-world contexts will have important implications for designing interventions to promote physical activity regulation.

For cognitive training to be effective, it is important that training not only benefits the specific cognitive control abilities that are trained but that training can be transferred to other similar abilities (near transfer effects) as well as those more distally associated with the trained cognitive abilities (far transfer effects; (Barnett and Ceci, 2002). Evidence of the extent to which cognitive training improvements show positive transfer on real-world outcomes is variable (Hofmann et al., 2012; Wang et al., 2014). In general, transfer effects of cognitive training, and in particular far transfer, can be difficult to demonstrate. A majority of studies documenting transfer effects report positive transfer to tasks similar to the trained task (i.e., near transfer; Dahlin et al., 2009). Anguera et al. (2013) found that training on a multitasking video game customized for older adults led to positive changes in cognitive control abilities, with improvements comparable to those observed in younger adults who are habitual video-game players (see also Kramer et al., 1999c). This work suggests that customizing cognitive training programs to specific populations may increase the likelihood of observing transfer effects. There is some evidence of positive far transfer effects of cognitive training. For instance, Jaeggi et al. (2008) found that training on a working memory task (*n*back) transferred to improvements in fluid intelligence, and more time spent in training led to greater transfer effects on fluid intelligence (but see Harrison et al., 2013).

Emerging research suggests that training cognitive control abilities may translate to improved self-regulation, particularly for individuals with low executive function (see Hofmann et al., 2012). To date, no research has examined whether cognitive training may have transfer effects on the self-regulation of physical activity behavior. Nonetheless, evidence that increased executive ability for inhibition predicted short-term exercise participation in young adults (Hall et al., 2008), and evidence that multi-tasking and inhibition abilities were significant predictors of subsequent long-term exercise adherence through the mediation of self-efficacy (McAuley et al., 2011) suggests that training cognitive control abilities holds significant potential for improving self-regulation for physical activity. In a similar vein, findings from an exercise intervention that combined visio-spatial training with thought-suppression demonstrated a simultaneous increase in adherence to an exercise program designed with periodization, i.e., more frequent sessions over time (Oaten and Cheng, 2006).

Interventions designed to increase cognitive control with transfer to physical activity-specific regulation may be more effective if they included components such as, stationary or motion-based computerized training tasks that activate mind-body connections, or tasks that concurrently enhance cognitive processes and motor movements fundamental to autonomous physical activity training. Interventions that include dual activation of movement and reward systems may also be effective at increasing training transfer to physical activity-specific regulation. Further, the utility of cognitive training for physical activity regulation may be enhanced by tailoring programs to specific executive function deficits for particular exercise subpopulations. For instance, for sedentary individuals, training efforts could be focused on cognitive abilities (e.g., inhibition, strategic attention, task-switching) that transfer to improved self-regulatory skill for initiating and maintaining exercise, and for overriding temptations to remain sedentary whereas in frail older adults, training efforts could focus on balance or gait dual-task training that transfer to improved lower-body functioning. In sum, interventions that augment cognitive control abilities provide exciting and important new avenues for enhancing self-regulation capacities for physical activity.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH DIRECTIONS

It has become clear that multiple brain networks including the DMN, the fronto-parietal and cingulo-opercular networks involved in cognitive control, and brain regions and pathways associated with reward (vmPFC, amygdala, ventral and dorsal striatum, mesocortical and mesolimbic) are functionally interconnected in the service of self-regulation. Neural activity associated with cognitive control is orchestrated by prefrontal regions. In accord with Hall and Fong (2010, 2013) temporal self-regulation theory, it appears that differences in executive control abilities and in the efficiencies of cognitive control networks that drive them, play a primary role in how well people are able to direct their attention to goal relevant information whilst restricting or inhibiting attention to competing goals, impulses, intrusive thoughts or emotions. These differences correlate with variability in self-regulation capacity. From this perspective, self-regulation is construed as behavioral manifestations of cognitive control processes (see also Nes et al., 2009; Kaplan and Berman, 2010; Hofmann et al., 2012). It is also clear that cognitive control abilities play a consequential role in the self-regulation of physical activity and sedentary behavior. Appropriate allocation of attentional resources and flexible cognitive control may be essential for maintaining a less sedentary and more physically active lifestyle. Although exercise self-regulation success is enhanced by supportive social networks and by environments that contain cues that encourage physical activity, without a functional threshold of cognitive control efficiency, individuals' attempts to process new exercise information, resist inactivity urges, overcome mental fatigue during exercise, and reprioritize plans to continue an exercise program are unlikely to be successful.

Training cognitive control abilities holds significant potential for improving self-regulation in sedentary individuals. Indeed, greater reductions in sedentary behavior are more likely to be realized by the addition of cognitive training components to interventions designed to decrease sedentary behaviors and increase physical activity. Given that cognitive control abilities work in concert to facilitate multiple aspects of self-regulation, optimizing cognitive control capacities will necessarily depend not only on exercising particular executive functions but training them in a coordinated fashion that involve interactions among individual capacities.

Despite recent advances, we do not fully understand the cognitive mechanisms that lead to successful exercise self-regulation and those that precipitate self-regulation failures that predispose people to remain sedentary. In particular, there is a pressing need to further identify the coordinated neural networks, which underlie the cognitive control of physical activity regulation. Increasing the utilization of individual differences approaches in future studies would advance our understanding of what aspects of cognitive control and neural systems are compromised in sedentary individuals. Greater knowledge of cognitive control deficits that underlie sedentary behavior would improve future intervention efforts to increase exercise self-regulation in regularly sedentary individuals. Identifying structural changes in the brain and the neural mechanisms of neuroplasticity by which cortical representations are functionally remodeled as a consequence of cognitive training, and, how these changes correlate with observable self-regulatory behavior is another potential avenue for future research. Further, future studies using longitudinal designs are required to gain insight on causal relations between cognitive control and self-regulation success and failure for physical activity.

The present review presented emerging research demonstrating the instrumental role of cognitive control abilities in self-regulation success and failure for physical activity. Additionally, neural networks that may underpin the cognitive control of physical activity and sedentary behavior were proposed. Cognitive training interventions for physical activity and key components of training program that may yield positive cognitive outcomes associated with increased physical activity were reviewed. The integration of exercise neuroscience and behavioral medicine fields holds significant potential to generate new knowledge that can be used to enhance cognitive control abilities that increase self-regulation capacity for physical activity.

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Temporal self-regulation theory: a neurobiologically informed model for physical activity behavior

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Dominant explanatory models for physical activity behavior are limited by the exclusion of several important components, including temporal dynamics, ecological forces, and neurobiological factors. The latter may be a critical omission, given the relevance of several aspects of cognitive function for the self-regulatory processes that are likely required for consistent implementation of physical activity behavior in everyday life. This narrative review introduces temporal self-regulation theory (TST; Hall and Fong, 2007, 2013) as a new explanatory model for physical activity behavior. Important features of the model include consideration of the default status of the physical activity behavior, as well as the disproportionate influence of temporally proximal behavioral contingencies. Most importantly, the TST model proposes positive feedback loops linking executive function (EF) and the performance of physical activity behavior. Specifically, those with relatively stronger executive control (and optimized brain structures supporting it, such as the dorsolateral prefrontal cortex (PFC)) are able to implement physical activity with more consistency than others, which in turn serves to strengthen the executive control network itself. The TST model has the potential to explain everyday variants of incidental physical activity, sport-related excellence via capacity for deliberate practice, and variability in the propensity to schedule and implement exercise routines.

Keywords: executive function, exercise, theoretical neuroscience, brain, behavior

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Temporal Self-Regulation Theory: A Neurobiologically Informed Model for Physical Activity Behavior

Physical activity promotion is of central interest to the fields of medicine and public health, as the prevention of chronic disease occurrence (primary prevention) and management of early onset (secondary prevention) both rely on it. Yet in order to increase physical activity behavior in the interests of disease prevention, it is necessary to have a firm understanding of the causal determinants of physical activity behavior itself. Such understanding in turn relies on iterative cycles of theory building, empirical testing and continued theory refinement. Our current theoretical models of physical activity behaviors largely mirror those of other health related behaviors, and have been drawn from applied social psychology, and to a lesser extent, clinical psychology and public health. Among the most well-known theories of physical activity behavior are the Transtheoretical Model (TTM; Prochaska et al., 1992) and the Theory of Reasoned Action/Planned Behavior (TPB; Ajzen and Madden, 1986).

Despite their initial popularity and apparent pragmatic appeal, these models have been criticized on a number of fronts, including their conceptual and epistemic foundations, empirical evidence base and ultimate testability (see Sutton, 1998; Ogden, 2003; West, 2005). Beyond these well-articulated criticisms, there is reason to believe that all of these models are also incomplete due to their non-inclusion of several categories of influence on difficult-to-implement behaviors such as physical activity. For instance, a substantial body of findings has emerged over the past decade or two regarding ecological influences on physical activity behavior (Sallis et al., 2006), as well as behavioral economic literatures highlighting the importance of temporal dynamics in decision making about behaviors that involve endurance of inconvenience or other costs, despite long-term cumulative benefits (Ainslie, 2013). Relatedly—and of most central consideration here—neurobiological aspects of self-regulatory processes are omitted entirely from both historic and contemporary models of physical activity behavior that have dominated the theoretical landscape in recent history. A growing body of literature, for example, identifies executive function (EF) as an important determinant of behaviors that require effort, consistency, and suspension of competing default behaviors (Hinkin et al., 2002, 2004; Hall et al., 2006; Insel et al., 2006; Hofmann et al., 2009, 2012; Allan et al., 2010; Nederkoorn et al., 2010; Stilley et al., 2010; Hall, 2012; Lowe et al., 2014). Effort, consistency and suspension of default preferences also seems characteristic of habitually implemented physical activity behavior, yet none of the current models include neurobiological factors that would theoretically facilitate the above.

Executive Function in Health Behavior Theory

EF can be defined as a set of cognitive processes that serve to enable reflective, "top-down" (as contrasted with reflexive, "bottom-up") control over behavior, thought and emotion, arising from the operation of distributed brain networks, with important nodes in the prefrontal cortex (PFC; Shallice and Burgess, 1993; Baddeley, 1996; Miller, 2000; Miyake et al., 2000; Miller and Cohen, 2001; Hofmann et al., 2012; Miyake and Friedman, 2012). The PFC is implicated in each of the three major subcomponents of EF, including working memory (i.e., the ability to work with finite information in an online state), inhibition (i.e., the ability to suspend prepotent responses), and mental flexibility (i.e., the ability to efficiently adapt to changing performance rules). Perhaps even more important than its status as a central (though non-exclusive; Van der Werf et al., 2003; Bellebaum and Daum, 2007) node in the executive control network is the PFC's extensive connections with other centers that drive more reflexive processes, thus enabling effective modulation of such centers more directly than would otherwise be possible (Miller and Cohen, 2001; Tekin and Cummings, 2002).

For example, the PFC is extensively interconnected with reward centers of the brain, which are evolutionally much older and more primitive than the neocortex (Groenewegen et al., 1997; Tekin and Cummings, 2002). This interconnectedness is especially important when explaining the potential for humans to forgo momentary pleasure, or reflexive reactions to the immediate environment, in the interests of other benefits that might be more long term in nature (Miller and Cohen, 2001; Hare et al., 2009; Figner et al., 2010; Luo et al., 2012). The ability to participate in physical activity behavior repeatedly for the sake of non-immediate benefits (i.e., disease/disability prevention, appearance or emotional benefits not manifest at the time of performance) is arguably one of the more important aspects of physical activity execution. While the experience of engaging in physical activity may be pleasurable, the lead up to initiation of each bout often involves forgoing more hedonically pleasurable activities (see **Figure 1**), and for new initiators, even the exercise experience itself may not be especially pleasurable until sufficient aerobic/muscular fitness has been built up, and until a certain level of confidence in one's abilities has been reached (Hall and Fong, 2007). Even activity in the form of sport participation that is experienced as "fun" by participants requires endurance of significant exertion, time cost, and even outright discomfort. Competitive sport, arguably even more so, requires commitment to endurance of long hours of practice not experienced as pleasurable by any except the most masochistic. Indeed, some argue that it is the capacity for such practice that may explain success in competitive sport more so than innate ability (Ericsson et al., 1993; Ericsson, 2014).

Beyond forgoing immediate pleasures, there are some specific benefits enabled by each of the facets of EF that are relevant to maintaining patterns of difficult-to-implement behaviors such as physical activity. First, the ability to keep activity goals in mind during decision making, or while engaged in other tasks, is enabled by working memory. Second, those with stronger inhibitory capacities may be better able to remember and implement physical activity plans in place of more compelling or immediately rewarding activities. And finally, mental flexibility may facilitate flexible adaptation of such plans to changing circumstances throughout the day, week or month, thereby enabling more consistent physical activity participation in the long run. Of the three facets of EF, arguably inhibition is the most central (Miyake and Friedman, 2012). Behavioral inhibition can be defined as the capacity to suspend prepotent responses to stimuli, and enables the possibility of behaving in ways that are counter to habit, visceral impulse, or social norms. For sedentary individuals, having relatively strong EF may be required to behave in active ways despite habitual non-activity, despite the appeal of maintaining inactivity, and contrary to peer and family norms which may reinforce inactivity directly or indirectly.

More importantly, there is potential for EF and physical activity to be functionally connected through positive and negative feedback loops over time. There is now a substantial literature of experimental studies demonstrating that participation in physical exercise improves EF (Kramer et al., 1999; Colcombe and Kramer, 2003; Colcombe et al., 2004; Liu-Ambrose et al., 2010; Smith et al., 2010; Davis et al., 2011). Likewise, there is now literature supporting the potential for EF to reinforce physical tactivity participation; for example,

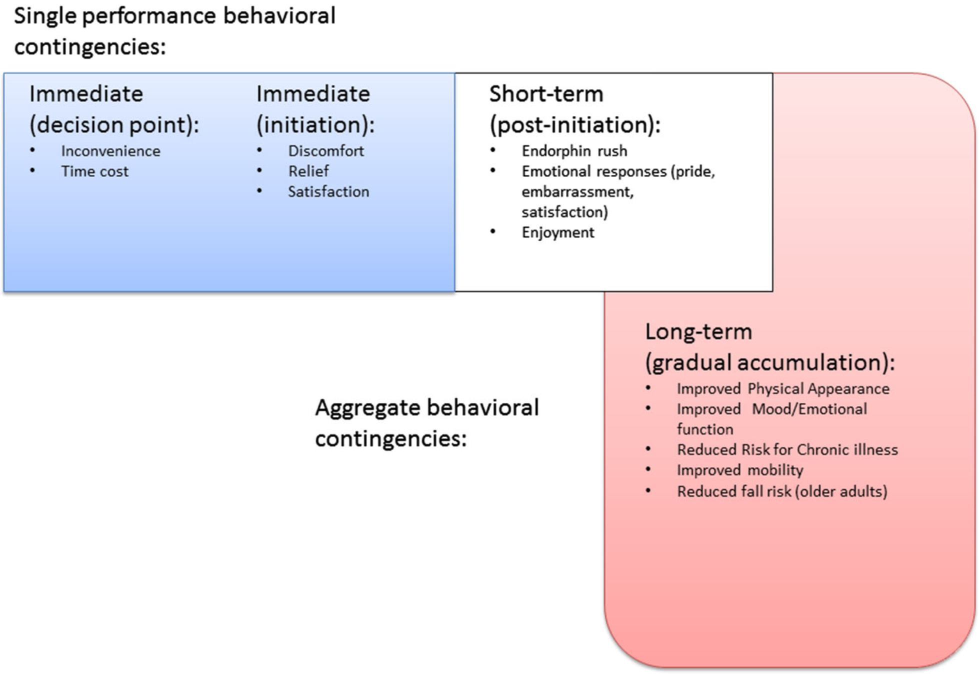

FIGURE 1 | Timeline of behavioral contingencies for physical activity behavior.

a recent study by Best et al. from this section found that participants in structured exercise programming were more likely to adhere to physical activity following conclusion of the structured programming if they experienced EF gains during the intervention period (Best et al., 2014). Likewise, Daly et al. showed time lagged associations between EF and physical activity participation that support the contention that they are mutually reinforcing over time (Daly et al., 2015). Finally, McAuley et al. (2011) demonstrated that EF predicted exercise class attendance via self-efficacy beliefs in the context of an exercise trial over the course of a 1-year interval among older adults. Together these studies provide preliminary evidence supporting the existence of positive and negative feedback loops involving physical activity and EF strength.

Given the conceptual role that EF plays in self-regulatory processes involved in repeated participation in physical activity over time, it seems sensible that it should have a role that is fairly central in theoretical models for physical activity behavior. The inclusion of EF in turn has the benefit of linking physical activity promotion—and the broader enterprise of health behavior change—with the larger human neuroscience literature on self-regulatory processes (Hofmann et al., 2012; Ochsner et al., 2012).

Temporal Self-Regulation Theory

Temporal self-regulation theory (TST; **Figure 2**) was introduced to account for the limitations of some of the existing social cognitive models of health behavior, including the lack of neurobiological factors such as EF (Hall and Fong, 2007, 2013). Briefly, the model posits that there are three proximal determinants of behavior: intention, prepotency and EF. The proximal model is in turn modulated by the ecological context, such that EF and prepotency become increasingly important causal links under conditions where the behavior is performed in an unsupportive environment (i.e., where there is large disjunction between when the costs and benefits for the behavior are incurred). In the absence of such temporal disjunction—a purely theoretical state of affairs that rarely exists for health related behaviors—the intention-behavior link would be assumed to be uniform and not moderated by prepotency or executive control (i.e., intentions are perfectly translatable into behavior). Intention in turn is determined by beliefs and values attached to the behavior based on many sources, including personal history with the behavior, but also other exogenous forces.

Proximal Model

One of the central facets of the TST model that it retains from earlier social cognitive models is the presence of intention as determinant of physical activity behavior. However, it is thought that the intention behavior link is subject to modification by both EF and behavioral prepotency (see above). Each of these has substantial empirical precedent from the experimental research literature (Webb and Sheeran, 2006; Jansen et al., 2013). Prepotency of physical activity behavior could be influenced by the extent to which physical activity is considered to be normative in the social environment ("norm"), strength of established habit to be either active or inactive ("habit"), or drive states that either facilitate or interfere with physical activity

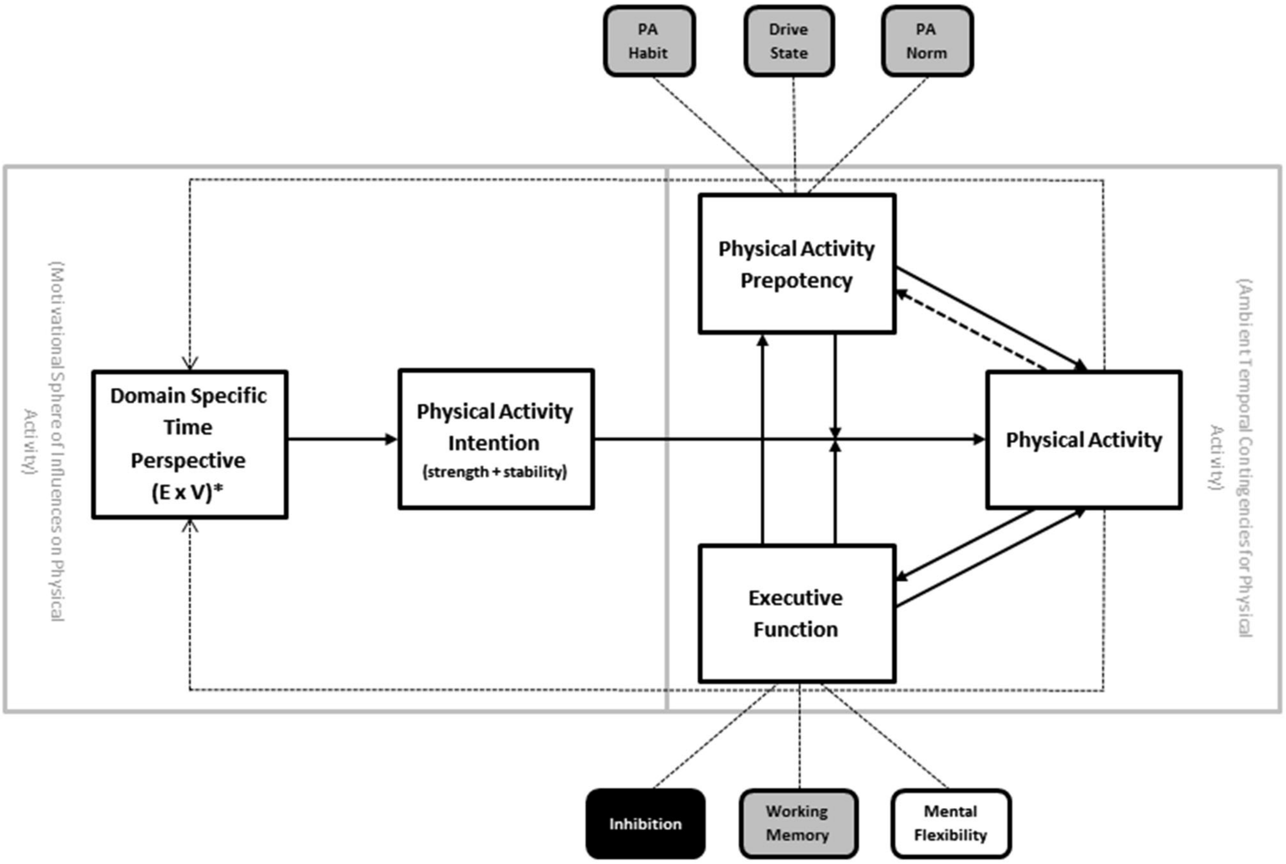

FIGURE 2 | Temporal self-regulation theory for physical activity (TST-PA). Note: PA = physical activity. Solid arrows indicate major causal pathways; dotted lines represent secondary causal pathways representing cumulative effects over time. * = temporally weighted.

(“drive”). In the case of physical activity (as opposed to other behaviors) it is assumed that norm and habit are stronger determinants of prepotency than drive states (whereas drive state may indeed be more influential for other behaviors that are more viscerally determined, such as substance use and dietary behavior).

Feedback Loops

Other facets of the proximal portion of the model are the addition of recursive feedback loops between physical activity behavior and both prepotency and EF. The recursive links back to prepotency are thought to be driven by the gradual cementing of physical activity habit strength and norm enhancement that would occur with repeated physical activity performance over time. The recursive link back to EF is based on the now extensive literature linking exercise training to enhancement of brain regions that support EF (Colcombe and Kramer, 2003; Smith et al., 2010), and more recent studies document the relationship between EF and physical activity implementation (McAuley et al., 2011; Best et al., 2014; Daly et al., 2015). Of additional interest is the link between EF and prepotency, reflecting the potential of strong EF to derail norm and habit driven inactivity in the interests of introducing physical activity behavior despite low behavioral precedent.

Contextual Modeling

Ambient temporal contingencies are the final component of the proximal model, and these reflect the degree of temporal disjunction between costs and benefits of a behavior imposed by the ecological context in which the behavior occurs. The higher the temporal dispersion of costs vs. benefits, the greater the requirement for self-regulation. For instance, examples of physical activity that include many immediate costs (e.g., inconvenience, time costs, monetary costs) but very gradual or delayed benefits (e.g., improved appearance, acceptance from peers, improved mobility), would tend to rely on self-regulatory processes involving EF, intention, and prepotency. Those instances of activity that have costs and benefits that fall around the same point in time might be more pure manifestations of simple decision making rather than self-regulation *per se* (e.g., the decision to join a game of basketball while already on the court with no competing time requirements). Because of the nature of physical activity and the range of ecological environments in the modern world, it is assumed that on balance there is a temporal dispersion of costs and benefits for activity, such that costs are relatively immediate and benefits are delayed or accumulate gradually after repeated performance. Different ecological parameters can amplify or reduce this temporal dispersion, by removing barriers or increasing ease of access to physical activity performance opportunities, for example.

Further back in the model, TST proposes determinants of intention itself, which are thought to be reducible to temporally anchored perceptions of expectancy and value. The latter parameter is assumed to be hyperbolic in relation to time such that outcomes that are temporally nearer are of more value, with immediacy associated with a very sharp spike in value (**Figure 3**, adapted from Ainslie, 2013). This hyperbolic shape to the value curve explains the tendency for preference reversals to occur (i.e., the tendency to make resolutions to be active on New Year's Eve, but then when facing the time to attend the first fitness class, preferring a competing sedentary activity instead).

Comparing and Contrasting TST with Existing Models

There are a few features that TST shares with existing models. First, there is a role for intention as a determinant of behavior. This is one feature that TST shares in common with TPB, as well as—to some extent—Social Cognitive Theory (Bandura, 1986), which also posits motivation as an important determinant of behavior. Additionally, like TPB, there is an upstream role for beliefs about possible outcomes of behavior. Finally, like TPB, there is a control related variable, though it is not perceived control *per se*, but rather, neurobiologically-based control resources that emanate from the operation of the PFC and its interconnectivity with more reflexive brain centers (the striatum and the limbic system).

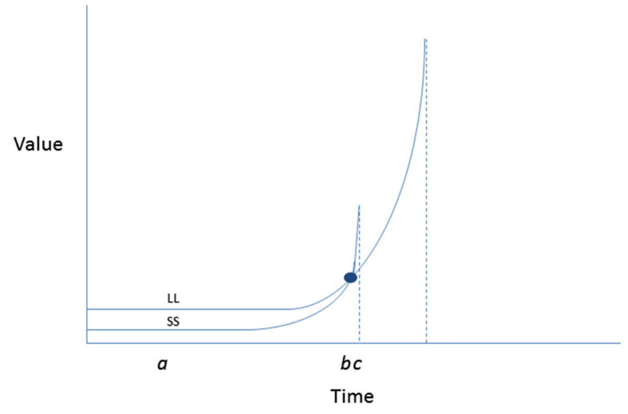

FIGURE 3 | Inverted hyperbolic discount curves illustrating a preference reversal involving forgoing larger later (health benefits, improved appearance) for smaller sooner (convenience, indulgence) contingencies when choosing between exercise and a competing enjoyable activity, such as video game playing. The y axis depicts subjective value of a reward associated with each of the activities at each time point. The *x* axis depicts the relative immediacy of receipt of each reward. At point a when both rewards are removed in time, the LL rewards of physical activity are preferred (i.e., have higher subjective value) than the SS rewards of computer game playing. However, with passage of time as SS becomes more immediately available, a spike in value is experienced. At b an indifference point is reached at wherein the value of SS (video game playing) and LL (exercising) are equivalent; at point c, with video game playing immediately available, its subjective value surges past that of exercise (despite having been initially less preferred). Adapted from Ainslie (2013).

Points of departure from existing models include the explicit use of temporal proximity as a determinant of the potency of both behavioral outcomes that are anticipated cognitively, as well as the relative influence (in a strict behaviorist sense) of contingencies encountered in the ecological context in which physical activity is performed. Such temporal contingencies (imagined and real) are central to the TST model vis-à-vis setting the stage for self-regulatory processes that take over where decision making leaves off. It is further assumed by the TST that the shape of the value curve for behavioral outcomes (real and imagined) is hyperbolic, as per Ainslie (2013). This is a well documented phenomenon, which explains the tendency for individuals deciding between two options (a smaller sooner (SS) reward and a larger later reward (LL)), to revert from preference for the LL reward in favor of the SS reward when the latter becomes imminent.

The dynamics of these choices refer to the nature of the values attached to each alternative. Essentially the preference reversal potentiates behavior that is counter to initially formed intention as the availability of the tempting alternative becomes more imminently available. In terms of physical activity, there are certainly many competing alternative behaviors, only one of which is video game playing. This however, is a highly prototypic example, given that these two behaviors do seem to compete especially in younger adults and children (Barnett et al., 2010).

Importantly, the preference reversal described above does not necessitate a behavioral reversal, but merely makes it more likely, given the partial dependence of behavior on value/preference. Active self-regulation counter to currently experienced value change amounts to active self-regulation, and within the TST model, can be withstood with enough behavioral precedent, and with enough executive control. That is, both prepotency of prior exercise experience and well developed EF can maintain the stability of intention to exercise in the presence of the immediately available, and more tempting alternative behavior. Indeed studies have shown that choosing the LL reward over the SS reward is associated with greater activation in the prefrontal areas of the cortex that support EF (Luo et al., 2012).

Applying TST to Model Physical Activity Promotion

There are several maxims that can be derived from TST when applied to physical activity promotion, some of which align with current best practices, and others that are more novel:

1. *Improve temporal balancing of costs and benefits associated with exercise*. Generally, physical activity performance brings immediately felt costs (time, convenience), and gradual accumulation of benefits (appearance, health). For some,

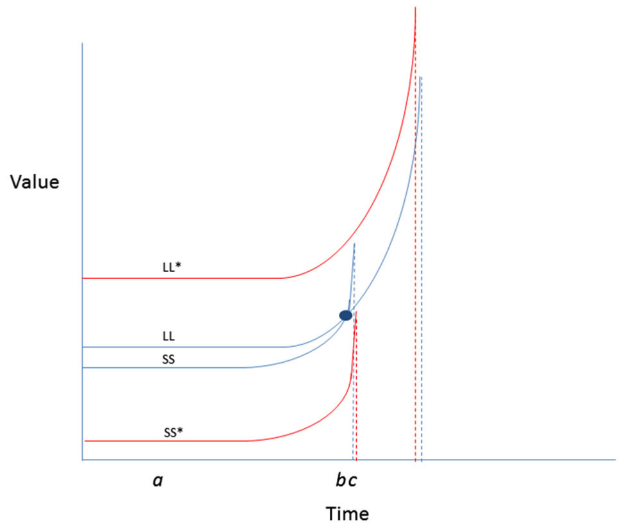

FIGURE 4 | Two possibilities for behavior change are presented: enhancing LL value or reducing SS value change. Enhancing the values attached to physical activity outcomes (by increasing salience, or making them more vivid) could raise the value curve (LL*) such that it no longer crosses the SS curve. Likewise, reducing the value of video games (by making them more difficult to access, or less normative) until the window of availability passes, could reduce temptation. Simultaneous enhancement of LL and reduction of SS could be the most efficient means for reducing likelihood of preference reversal in favor of a competing sedentary behavior.

the experience of performance is also pleasurable, once initiated. Amplifying these pleasurable aspects of experience, and making them salient at choice time may be helpful. Likewise, some categories of immediate cost can be mitigated; for instance, removing or reducing the monetary cost associated with activity (for instance by subsidizing facility memberships) may assist inactive people in need to become more active, and be guided by non-immediate benefits. Improving accessibility of venues and equipment necessary to exercise may also provide benefit in this respect.

2. *Optimize executive function*. Removing the influence of agents that reduce EF, such as sleep deprivation, alcohol and stress may serve to optimize the cognitive control mechanisms that are essential for implementing physical activity plans that have already been formed. Once activity begins in earnest, there could be a feed forward benefit of physical activity on EF that might render subsequent activity implementation more consistent, and less draining of personal resources.

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3. *Induce intention strength and stability* by emphasizing, and rendering salient at crucial choice points, the expected cumulative benefits of physical activity. Often these are known intellectually in a remote sense, but are crowded out by other thoughts at times when decisions about activity are being made.
4. *Amplify valuations* and expectancies for exercise, and mitigate costs. Although the hyperbolic discount curves that characterize outcomes as a function of immediacy may suggest that rewarding sedentary activities may be more valued, there are some possible ways of improving the expectancy-value landscape for energy burning forms of physical activity. Some of the theoretical possibilities are represented in **Figure 4**. As depicted in the example, encouraging greater spread in value curves separating exercise from a competing alternative sedentary behavior could reduce the likelihood of preference reversals in favor of the latter.
5. Encouragement of physical activity requires *multi-level action*, ranging from policy and built environment to individual behavior change in order to facilitate implementation, in much the same way we need to exploit these same routes for other behavioral imperatives for disease prevention (Marteau et al., 2012; Marteau and Hall, 2013).

Summary

TST conceptualizes physical activity behavior as being centrally influenced by intention strength/stability, behavioral prepotency and EF. The latter is particularly central, and yet it has not previously been incorporated into any formal model for physical activity behavior. The TST model hypothesizes mutual reinforcement of EF and physical activity over time, a self-regulatory loop supported by several empirical studies in this section. Research supporting both the implementation-facilitating effects of EF on other difficult-to-implement health behaviors, and the effects of physical activity on brain systems that support EF, are both buttressed by findings from individual experimental studies and, in some cases, meta-analytic summaries of such work. Future research may inform the specificity of the TST model in relation to physical activity by identifying critical thresholds of EF and physical activity required to achieve self-perpetuation of the EF-activity cycle over time. Establishing such thresholds would constitute a key step in establishing the required prescriptive dose to enhance likelihood of long-term maintenance of physical activity behavior in the general population.

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The influence of cardiorespiratory fitness on strategic, behavioral, and electrophysiological indices of arithmetic cognition in preadolescent children

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The current study investigated the influence of cardiorespiratory fitness on arithmetic cognition in forty 9–10 year old children. Measures included a standardized mathematics achievement test to assess conceptual and computational knowledge, self-reported strategy selection, and an experimental arithmetic verification task (including small and large addition problems), which afforded the measurement of event-related brain potentials (ERPs). No differences in math achievement were observed as a function of fitness level, but all children performed better on math concepts relative to math computation. Higher fit children reported using retrieval more often to solve large arithmetic problems, relative to lower fit children. During the arithmetic verification task, higher fit children exhibited superior performance for large problems, as evidenced by greater *d'* scores, while all children exhibited decreased accuracy and longer reaction time for large relative to small problems, and incorrect relative to correct solutions. On the electrophysiological level, modulations of early (P1, N170) and late ERP components (P3, N400) were observed as a function of problem size and solution correctness. Higher fit children exhibited selective modulations for N170, P3, and N400 amplitude relative to lower fit children, suggesting that fitness influences symbolic encoding, attentional resource allocation and semantic processing during arithmetic tasks. The current study contributes to the fitness-cognition literature by demonstrating that the benefits of cardiorespiratory fitness extend to arithmetic cognition, which has important implications for the educational environment and the context of learning.

Keywords: addition, pediatric-cognition, strategy, ERPs, mathematics

INTRODUCTION

Recent research suggests that cardiorespiratory fitness and physical activity (PA) are positively associated with neurocognitive health across the lifespan (Colcombe et al., 2004a,b; Hillman et al., 2005, 2006; Kramer et al., 2006; Pontifex et al., 2009; Smith et al., 2010; Erickson et al., 2011; see Hillman et al., 2008 for review), but the majority of research has focused on adult populations with fewer efforts directed toward understanding the relation of cardiorespiratory fitness and PA to neurocognition during development. As children have become increasingly sedentary and opportunities for PA during the school day have diminished (Institute of Medicine of the National Academies, 2013), illuminating the neurocognitive benefits resulting from cardiorespiratory fitness and PA have never been more important. What research exists indicates that cardiorespiratory fitness and PA are also positively associated with neurocognition during development, with disproportionate benefits witnessed on the behavioral and neural levels for tasks requiring variable amounts of attention and cognitive control (Hillman et al., 2005, 2009; Buck et al., 2008; Chaddock et al., 2011; Pontifex et al., 2011; Voss et al., 2011; Moore et al., 2013). However, the specificity of the relation between cardiorespiratory fitness and PA in developing populations continues to unfold (Tomporowski, 2003; Sibley and Etnier, 2003; Castelli et al., 2007; Buck et al., 2008; Hillman et al., 2009; Pontifex et al., 2011; Moore et al., 2013).

One area receiving increasing attention is the relation of cardiorespiratory fitness to academic achievement. Both larger-scale cross-sectional (California Department of Education, 2001, 2005; Cottrell et al., 2007; Chomitz et al., 2009), and smaller-scale experimental studies (Castelli et al., 2007; Wittberg et al., 2012) have found a positive relation of fitness to linguistic and arithmetic indices of academic achievement. Arithmetic achievement is of particular interest given that arithmetic cognition is a fundamental skill in modern society, plays an important role in everyday life (Rips et al., 2008; Chen et al., 2013) and is a critical skill set for children to master (El Yagoubi et al., 2005; Menon, 2010). Recently, research efforts have been directed toward understanding the development of arithmetic proficiency on both the behavioral and neural level to understand how this skill set is acquired and effectively maintained across the lifespan (Rips et al., 2008; Imbo and Vandierendonck, 2008; Chen et al., 2013). While several demographic and health factors have been found to mediate arithmetic development and achievement (White, 1982; Geary et al., 2004; Sirin, 2005; Castelli et al., 2007; Chomitz et al., 2009), in general, the development of arithmetic proficiency is characterized by a shift in strategy selection from effortful, inefficient strategies to more automated and efficient strategies (Siegler, 1986). Thus, arithmetic proficiency is contingent on both strategy selection and strategy efficiency (Imbo and Vandierendonck, 2008).

Strategy selection refers to the procedure necessary to solve a problem, and strategy efficiency refers to the speed and accuracy at which a solution is produced or verified (Imbo and Vandierendonck, 2008). Children typically rely on one of three strategies to solve arithmetic problems: (1) finger and verbal counting, which are effortful and less efficient strategies used during initial learning, (2) decomposition (i.e., $8 + 7 = 5 + 3 + 5 + 2$), and (3) retrieval. These last two strategies are more automated and efficient, and are characteristic of increasing arithmetic skill (Ashcraft, 1982; Siegler, 1986; Roussel et al., 2002; Imbo and Vandierendonck, 2008; Cho et al., 2011). Accordingly, the developmental shift from finger and verbal counting to decomposition and retrieval strategies leads to quicker and more accurate solution production and verification (Geary et al., 2004; Imbo and Vandierendonck, 2008). This shift in strategy is most evident in the second and third grades (Ashcraft and Fierman, 1982; Geary et al., 1987, 2004), and is contingent on the development of children's conceptual understanding of counting (Siegler, 1987; Geary et al., 2004), phonological abilities (De Smedt et al., 2010), and the development of semantic memory networks between problem stems and solutions (Siegler and Shrager, 1984; Cho et al., 2011).

In addition to standardized achievement tests, the arithmetic verification task has been of particular utility for revealing behavioral and neural processes associated with arithmetic calculation across the lifespan (Niedeggen et al., 1999; El Yagoubi et al., 2003; Galfano et al., 2004; Jost et al., 2004; Núñez-Peña et al., 2006, 2011; Xuan et al., 2007; Imbo and Vandierendonck, 2008; De Smedt et al., 2010; Prieto-Corona et al., 2010). During arithmetic verification tasks, individuals are presented with problems in the form of $a + b = c$, and must verify whether the solution is correct or incorrect. On the behavioral level, solution verification has been characterized by longer RT and decreased accuracy (ACC) for incorrect relative to correct solutions (Niedeggen and Rosler, 1999; Campbell and Fugelsang, 2001; Domahs and Delazer, 2005; Jasinski and Coch, 2012); a phenomenon known as the split effect. Solution verification has also been characterized by longer RT and decreased ACC for large (>10) relative to small (<10) solutions (Groen and Parkman, 1972; Zbrodoff and Logan, 2005; Imbo and Vandierendonck, 2008; Núñez-Peña et al., 2011); a phenomenon known as the problem size effect. Thus, verification tasks enable the evaluation of arithmetic processes across multiple dimensions of difficulty (i.e., correctness, size).

Electroencephalography (EEG) and event-related potential in particular (ERPs) have proven to be an invaluable tool for evaluating the neural underpinnings of arithmetic cognition (El Yagoubi et al., 2005; Muluh, 2011; Jasinski and Coch, 2012). During arithmetic verification, ERPs time-locked to solution presentation reliably reveal a P3, N400-like negativity, and a late positive component (LPC) in adults. The arithmetic P3 is larger for correct relative to incorrect solutions (Niedeggen et al., 1999; Galfano et al., 2004; Jost et al., 2004; Núñez-Peña et al., 2011; Jasinski and Coch, 2012) and has been linked to the classic P3b, (Niedeggen et al., 1999; Jost et al., 2004). The arithmetic N400 is larger for incorrect, relative to correct solutions (Niedeggen et al., 1999; Jost et al., 2004; Prieto-Corona et al., 2010; Jasinski and Coch, 2012), and has been linked to the N400 observed in other paradigms, suggesting that it is an index of semantic information processing (Kutas and Federmeier, 2000, 2011; Federmeier and Laszlo, 2009). The LPC is larger for incorrect relative to correct solutions and is hypothesized to be an index of plausibility processing (i.e., given $a + b$, is solution c reasonable?; Niedeggen et al., 1999; Jost et al., 2004; Domahs et al., 2007; Jasinski and Coch, 2012); linking this component to the P600 (Núñez-Peña and Honrubia-Serrano, 2004; Núñez-Peña et al., 2004). In addition, earlier ERP components such as the N1/N170 have been systematically modulated during numerical paradigms (Dehaene, 1996; Szũcs and Goswami, 2007; Hyde and Spelke, 2009, 2012; Palomares et al., 2011); however, the functional interpretation of these components remains controversial (Feigenson et al., 2004; Muluh, 2011; Heine et al., 2012) and seldom explored during arithmetic verification tasks (He et al., 2011; Muluh et al., 2011).

Despite numerous investigations examining the electrophysiological processes underlying arithmetic verification in adults, a paucity of data exists for children with only a few initial studies comparing children and adults (Xuan et al., 2007; Prieto-Corona et al., 2010). For example, Prieto-Corona et al. (2010) compared 8–10 year old children and young adults during a multiplication-verification task. In addition to longer RT and decreased ACC, the children exhibited larger N400 amplitude and longer N400 latency for incorrect solutions relative to adults. Further, adults, but not children, displayed a LPC during incorrect solution presentation. Thus, in addition to behavioral differences, children also quantitatively and qualitatively differ from adults on the electrophysiological level during arithmetic performance. As such, additional research is warranted to detail the neurodevelopmental shifts that give rise to mature arithmetic cognition, as well as the potential health factors, which may mediate this development.

The current study evaluated arithmetic performance in higher and lower fit children by employing both a standardized achievement test as well as an experimental addition-verification task, which consisted of small (<10) and large (>10) solutions, and afforded the measurement of electrophysiological activity. Furthermore, to assess strategy selection, participants were asked to report how they solved small and large addition problems, which appeared during both the standardized achievement assessment and experimental task. Irrespective of fitness, all children were expected to demonstrate longer RT and decreased ACC for incorrect relative to correct solutions, irrespective of solution size. It was also predicted that all children would demonstrate longer RT and decreased ACC for large relative to small solutions, irrespective of solution correctness; thus replicating prior work (Imbo and Vandierendonck, 2008; Prieto-Corona et al., 2010; Cho et al., 2011). Children were further expected to exhibit larger P3 amplitude for correct relative to incorrect solutions and larger N400 amplitude for incorrect relative to correct solutions. Based on prior work (Prieto-Corona et al., 2010), children were not expected to exhibit a LPC, indicative of a protracted development in plausibility processing.

With respect to fitness, higher fit children were expected to demonstrate superior performance for standardized math achievement and report more frequent use of retrieval than their lower fit counterparts. It was further expected that higher fit relative to lower fit children would demonstrate differences in performance on the behavioral and electrophysiological levels during the arithmetic verification task. Specifically, higher fit children were expected to respond more quickly and accurately during incorrect solutions across problem sizes, and this effect would be selectively greater for large problems. In addition, higher fit relative to lower fit children were predicted to demonstrate more flexible deployment of attention, as indexed by smaller P3 amplitude during small problem solutions and larger P3 amplitude during large problem solutions. Lastly, we predicted that higher fit children would demonstrate larger N400 amplitude during incorrect problem solutions indicating facilitated semantic access for discriminating between incorrect and correct solutions.

MATERIALS AND METHODS

PARTICIPANT CHARACTERISTICS

Forty preadolescent children aged 9–10, (16 female) were recruited from the East-Central Illinois region. Participants were bifurcated into higher (>70th percentile) or lower (<30th percentile) fitness groups based on age-specific norms (Shvartz and Reibold, 1990). Maximal aerobic capacity (VO_{2max}) was based on the volume of oxygen consumed during maximum capacity exercise ($ml/kg \cdot min^{-1}$). **Table 1** lists demographic and fitness information for the sample. No child received special education services related to mental or physical disabilities and all participants and their legal guardians provided written informed assent/consent in accordance with the Institutional Review Board at the University of Illinois.

Prior to testing, legal guardians completed a health history and demographics questionnaire, indicating that their child was free of neurological diseases or physical disabilities. The Kaufman Brief Intelligence Test 2 (KBIT-2; Kaufman and Kaufman, 2004) was administered to each participant to create a composite intelligence quotient (IQ). The Attention-Deficit Hyperactivity Disorder Rating Scale IV (DuPaul et al., 1998) was completed by guardians to screen for the presence of attentional disorders (as indexed by scores above 14 and 22 for females and males, respectively). In cooperation with the child, guardians completed a modified Tanner Staging System (Taylor et al., 2001) to assess pubertal timing. Subsequently, all participants were at or below a score of 2 (i.e., prepubescent) at time of testing. In addition, SES was assessed by computing a trichotomous index based on three variables: (a) participation in a free or reduced-price lunch program at school; (b) the highest level of education obtained by the mother and father; and (c) number of parents who worked full time (Birnbaum et al., 2002). Lastly, all participants demonstrated right-handedness as measured by the Edinburgh Handedness Inventory (Oldfield, 1971).

Table 1 | Participant demographics data for higher and lower fit children.

Measure	Higher fit	Lower fit
Age (years)	9.9 (0.7)	10.1 (0.6)
Gender (M/F)	13/7	11/9
Grade	4.0 (0.8)	4.3 (0.6)
SES	2.0 (0.8)	2.4 (0.7)
Tanner	1.2 (0.3)	1.3 (0.4)
K-BIT	120.8 (11.5)	119.9 (11.8)
BMI percentile (%)	35.6 (28.1)	52.7 (32.0)
BMI	16.9 (3.5)	19.1 (4.7)
Vo2 percentile (%)*	82.7 (7.1)	28.1 (7.9)
Vo2 relative	52.7 (5.1)	41.43 (4.2)
Computation percentile (%)	76.8 (23.9)	77.8 (21.7)
Concepts percentile (%)	87.0 (12.1)	89.5 (17.0)
Composite percentile (%)	88.1 (13.8)	87.5 (16.1)

Tanner refers to the Tanner pubertal timing scale; SES, socio-economic status; K-BIT, Kaufmann Brief Intelligence Test; BMI, body mass index; VO2 refers to aerobic fitness; Computation, concepts, and composite refer to the sub-sections and combined composite score of the KTEA-2 achievement test. *$^{*}p < 0.05$.*

CARDIORESPIRATORY FITNESS ASSESSMENT

VO_{2max} was measured on a motor–driven treadmill using a modified Balke protocol, which is recommended for graded exercise testing with children (American College of Sports Medicine, 2010). Prior to testing, participants had their height and weight measured, were fitted with a Polar heart rate (HR) monitor (Polar Wear Link® + 31, Polar Electro, Finland), and underwent a brief warm-up period. The treadmill was then set to a constant speed during the test, while grade increments of 2.5% occurred every 2 min until volitional exhaustion. Oxygen consumption was measured using a computerized indirect calorimetry system (ParvoMedics True Max 2400) with averages for oxygen uptake and respiratory exchange ratio (RER) assessed every 20 s. Concurrently, ratings of perceived exertion (RPE) were measured every 2 min using the children's OMNI scale (Utter et al., 2002). VO_{2max} was established when children met a minimum of 2 of the following 4 criteria: (1) a plateau in oxygen uptake corresponding to an increase of less than 2 $ml/kg \cdot min^{-1}$ despite an increase in exercise workload; (2) a peak HR $\geq$185 beats per minute (bpm; American College of Sports Medicine, 2010) and a HR plateau (Freedson and Goodman, 1993); (3) RER $\geq$1.0 (Bar-Or, 1983); and/or (4) ratings on the children's OMNI scale of perceived exertion $\geq$8 (Utter et al., 2002). Relative peak oxygen consumption was expressed in milliliters of oxygen consumed per kilogram of body weight per minute.

EEG RECORDING

Electroencephalographic (EEG) activity was recorded from 64 sintered 10 mm Ag-AgCl electrodes (FPz, Fz, FCz, Cz, CPz, Pz, POz, Oz, FP1/2, F7/5/3/1/2/4/6/8, FT7/8, FC3/1/2/4, T7/8, C5/3/1/2/4/6, M1/2, TP7/8, CB1/2, P7/5/3/1/2/4/6/8, PO7/5/3/4/6/8, O1/2), arranged according to the International 10-10 system (Chatrian et al., 1985) using a Neuroscan Quik-cap (Compumedics, Inc, Charlotte, NC). EEG activity was referenced to averaged mastoids (M1, M2), with AFz serving as the ground electrode. Impedance was kept below 10 kΩ. Additional electrodes were placed above and below the left orbit and on the outer canthus of each eye to monitor electro-oculographic (EOG) activity with a bipolar recording. Continuous raw EEG data were collected using Neuroscan Scan software (v 4.5) and amplified through a Neuroscan Synamps 2 amplifier with a 24 bit A/D converter and ± 200 millivolt (μV) input range (763 μV/bit resolution). Data were sampled at a rate of 500 Hz and amplified 500 times with a DC to 70 Hz filter, and a 60 Hz notch filter.

TASKS

Achievement

Participants were administered the mathematics subsections of the Kaufman Test of Academic and Educational Achievement 2 (KTEA-2; Kaufman and Kaufman, 2004), which included tests of math concepts and computation. The subtest begins by testing concepts such as cardinality, ordinality, comparing quantities, as well as basic arithmetic and rounding. As problems increase in difficulty, algebraic, calculus, and trigonometry concepts are required. Participants were given a scratch paper and a pencil, but were not allowed to use a calculator. The math computation subsection is a 72-item subtest, which begins with basic arithmetic operations including: adding, subtracting, multiplying, and dividing whole numbers of increasing magnitude, as well as fractions. Later problems require calculations involving exponents, decimals, negatives, and unknown variables. Again, participants were provided with scratch paper and a pencil, but were not allowed to use a calculator. Participants' scores were entered into the normative age database to provide an achievement percentile score for each subtest as well as composite match achievement percentile score.

Arithmetic verification task

The current arithmetic verification task was modeled on parameters provided by Núñez-Peña and Suárez-Pellicioni (2012). However, given the younger age of children in the current study and preliminary pilot testing, the largest problem combinations from Núñez-Peña's paradigm were not employed. All problems were expressed in the form of $a + b = c$. For each problem two operand orders were created ($a + b = c$, $b + a = c$). Small problems used single-digit operands between 1 and 4 and large problems used single-digit operands between 6 and 9. Ties (e.g., $3 + 3$), and consecutive even operands (e.g., $2 + 4$) were excluded, and the solution was never the product of $a \times b$. For each problem and operand order, both a correct and incorrect solution were created with incorrect solutions being either lesser or greater by 1 than the correct solution. Thus, all incorrect solutions were small split, and parity was controlled.

Each trial consisted of stimuli presented sequentially in the following order: a fixation dot presented for 500 ms, the first operand presented for 1000 ms, a "+" sign presented for 500 ms, the second operand presented for 2000 ms, and then the solution, which was surrounded by a box and remained on the screen until the participant responded or a maximum of 2000 ms elapsed. The inter-stimulus interval was 100 ms and participants were instructed to respond as quickly and accurately as possible. Participants were counterbalanced according to correct response selection, with half of the participants instructed to make a right hand thumb press on a response pad if the solution was correct and the other half instructed to make a left thumb press if the solution was correct. Response assignments were further counterbalanced across fitness groupings. Participants completed two blocks of small problems and two blocks of large problems, which were counterbalanced across participants. Thus, all participants completed 240 trials, 120 for each problem set size, with 60 correct and 60 incorrect solutions presented randomly for each problem set size (see **Figure 1**).

LABORATORY PROCEDURE

Day 1

Participants and their guardians completed an informed assent and informed consent, respectively. Next, participants completed the Edinburgh Handedness Inventory followed the KBIT-2, which was administered by a trained experimenter. Participants then completed the mathematics portion of the KTEA-2. Concurrently, participants' legal guardians completed the health history and demographics questionnaire, the ADHD Rating Scale IV, the modified Tanner Staging System, and the Physical Activity Readiness Questionnaire (Thomas et al., 1992). Participants then had their height and weight measured and completed the cardiorespiratory fitness assessment. Upon completion, participants were afforded a cool down period and remained in the laboratory until their HR returned to within 10 beats per minute of their resting HR.

Day 2

Participants returned to the laboratory and were outfitted with an EEG cap before being seated in an electrically and acoustically attenuated testing chamber. Following the provision of instructions for the arithmetic verification task, participants were given the opportunity to ask questions, and then performed a practice block of 30 trials prior to each problem set size. The experimenter observed participants during the practice trials and checked their performance to ensure that they understood the task. If a participant's task performance was below 60%, another practice block was administered. Upon the completion of the task, participants

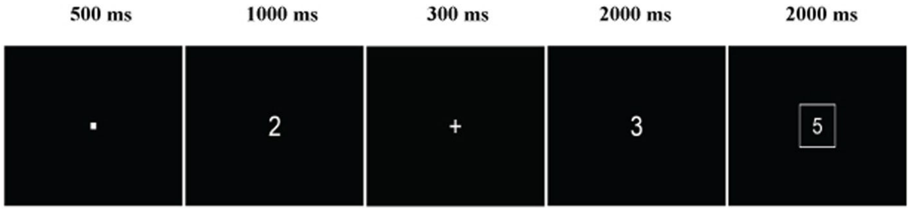

FIGURE 1 | Sample problem from the arithmetic verification task.

were briefed on the purpose of the experiment, and received \$10/h remuneration.

BEHAVIORAL DATA REDUCTION

Strategy

Children were asked to report how they solved a small and large addition problem during the computation portion of KTEA-2 achievement test. Similar to previous studies (Geary et al., 2004), children were asked "can you tell me how you got the answer?" and based on the child's response and experimenter's observation, responses were classified into three categories: counting (finger/verbal), decomposition ($4 + 7 = 4 + 5 + 2$), or retrieval ("just knew it"). Responses were coded as 1 for counting, 2 for decomposition, and 3 for retrieval. Thus, each participant received a score of 1, 2, or 3 per problem.

Mathematics achievement

A trained experimenter graded children's responses such that children received a 1 for each correct response and a 0 for an incorrect response. Scores were then tallied to generate a total score for each sub-section and entered into a normative database of values. Thus, each child received an age-normed achievement percentile for each sub-section, as well as a composite achievement percentile score.

Arithmetic verification task

Behavioral data were collected in terms of RT (time in milliseconds from stimulus presentation until manual response) for correct trials, and ACC (percentage of correct responses) for each task condition. In accord with previous research (Geary, 2010; Núñez-Peña and Suárez-Pellicioni, 2012), d' [z (hit rate) - z (false alarm rate)] scores were calculated for each problem size.

ELECTROPHYSIOLOGICAL DATA REDUCTION

Prior to averaging, an off-line EOG reduction procedure was applied to individual trials via a spatial filter (Compumedics Neuroscan, 2003), which performed a principle component analysis (PCA) to determine the major components that characterize the EOG artifact between all channels. This procedure then reconstructed the original channels without the artifact components (Compumedics Inc, Neuroscan, 2003). Trials with a response error or artifact exceeding $\pm 75\,\mu$V were rejected and artifact free data were retained for averaging. An average of 43 ($\pm$ 2) trials and 42 ($\pm$ 3) trials were retained for large-correct and large-incorrect solutions respectively, and 48 ($\pm$ 1) trials and 44 ($\pm$ 2) trials were retained for small-correct and small-incorrect solutions, respectively. Higher and lower fit participants did not differ in the number of trials retained for averaging, p's ≥ 0.83.

Stimulus-locked components were created using epochs from -100 to 1000 ms around solution stimuli and were baseline corrected using the 100-ms pre-stimulus period. Data were filtered with a zero phase shift 30-Hz low-pass cutoff (24 dB/octave rolloff). The P1 component was identified as the mean amplitude within a 30 ms interval surrounding the largest positive-going peak within 75–150 ms latency. The N170 component was identified as the mean amplitude within a 30 ms interval surrounding the largest negative-going peak within 100–200 ms latency. The P3 component was identified as the mean amplitude within a 50 ms interval surrounding the largest positive-going peak within 300–600 ms latency. The N400 component was identified as the mean amplitude within a 50 ms interval surrounding largest negative-going peak within 300–500 ms latency. Amplitude was measured as the difference between the mean pre-stimulus baseline and mean peak-interval amplitude; peak latency was defined as the time point corresponding to the maximum local peak amplitude.

STATISTICAL ANALYSIS

Statistical analyses were performed using SPSS version 19.0 (SPSS Inc., Chicago, IL) and statistical significance was noted when $p < 0.05$. Paired sample and independent samples t-tests were conducted to evaluate both academic achievement scores and strategy reports. Behavioral data were analyzed using a 2 (Group: higher fit, lower fit) $\times$ 2 (Correctness: correct, incorrect) $\times$ 2 (Problem Size: small, large) repeated-measures ANOVA for the arithmetic verification task, with fitness group entered as a between-subjects factor. In addition, d' scores for the arithmetic verification task were analyzed using a 2 (Group: higher fit, lower fit) $\times$ 2 (Problem Size: small, large) repeated-measures ANOVA. All ANOVAs used the Greenhouse-Geisser correction to correct for violations of sphericity and Bonferroni corrected t-tests were utilized to evaluate *post-hoc* significance.

Electrophysiological analysis was conducted separately on P1, N170, P3, and N400 component values (i.e., amplitude, latency). Similar to previous investigations (Prieto-Corona et al., 2010; Muluh et al., 2011; Núñez-Peña and Suárez-Pellicioni, 2012) regions of interest (ROIs) were created. Specifically, P1, N170, and P3 component values were formulated by averaging electrode sites into 3 regions: left (P7, PO7, P5, PO5, P3, PO3), center (P1, PZ, POZ, P2), and right (P8, PO8, P6, PO6, P4, PO4) using similar factorial models as described above with the addition of a region factor. Based on difference waves, N400 component values for each participant were analyzed by decomposing electrode sites into 2 ROI's: left (C5, CP5, P5, C3, CP3, P3, C1, CP1, P1) and right (C6, CP6, P6, C4, CP4, P4, C2, CP2, P2) and were submitted to similar factorial models as described above, with the addition of a region factor.

RESULTS

BEHAVIOR

Mathematics achievement

Achievement data are reported in **Table 1**. Analysis of achievement data revealed that all participants' scored significantly higher on the math concepts relative to the math computation section of the achievement test, [$t_{(39)} = 3.84$, $p < 0.01$]. No fitness group differences were realized for math computation, concepts, or composite achievement percentile, [$t'\text{s}_{(38)} \leq 0.36$, $p'\text{s} \geq 0.72$].

Strategy

Analysis of strategy revealed a main effect of problem size, indicating that all participants reported relying more on retrieval than procedural strategies (counting, decomposition) for small ($m = 2.9 \pm 0.5$) relative to large problems ($m = 2.5 \pm 0.7$), [$F_{(1,\ 38)} = 10.50$, $p < 0.01$, $\eta^2 = 0.21$]. However, this effect, was superseded by problem size × fitness interaction, [$F_{(1,\,38)} = 5.65$, $p = 0.02$, $\eta^2 = 0.13$]. *Post-hoc* analysis revealed a significant trend indicating that higher fit children reported relying on retrieval more frequently than lower fit children during large problem solutions, [$t_{(39)} = 2.30$, $p < 0.03$].

Arithmetic verification task

RT. Analysis revealed effects of problem size, [$F_{(1,\,38)} = 19.90$, $p < 0.01$, $\eta^2 = 0.34$], and correctness, [$F_{(1,\,38)} = 89.31$, $p < 0.01$, $\eta^2 = 0.70$], indicating that all participants responded more quickly to small ($m = 863.58 \pm 158.8$), relative to large ($m = 932.84 \pm 166.6$) problems, and for correct ($m = 838.82 \pm 170.9$) relative to incorrect ($m = 961.8 \pm 170.9$) problems. Analysis did not reveal any significant effects of fitness, [$F's_{(1,\,38)} \leq 1.89$, $p \geq 0.18$, $\eta's^2 \leq 0.05$].

ACC. Analysis revealed effects of problem size, [$F_{(1,\,38)} = 23.64$, $p < 0.01$, $\eta^2 = 0.38$], and correctness, [$F_{(1,\,38)} = 7.92$, $p < 0.01$, $\eta^2 = 0.17$], which were superseded by a problem size × correctness interaction, [$F_{(1,\,38)} = 5.71$, $p = 0.02$, $\eta^2 = 0.13$]. *Post-hoc* analysis revealed that all participants responded less accurately for large-incorrect problems ($m = 74.3 \pm 15.9$), relative to small-correct ($m = 84.7 \pm 8.4$), small-incorrect ($m = 81.7 \pm 10.8$), and large-correct ($m = 81.2 \pm 12.7$) problems, [$t's_{(38)} \geq 3.15$, $p < 0.01$]. No effect of fitness was observed, [$F's_{(1,\,38)} \leq 2.42$, $p's \geq 0.13$, $\eta 2's \leq 0.06$].

d'. Analysis revealed a main effect of problem size, [$F_{(39,\,1)} = 5.94$, $p = 0.02$, $\eta^2 = 0.14$], indicating that all participants were more accurate at detecting correct (and rejecting incorrect) solutions for small ($m = 2.7 \pm 0.5$) relative to large ($m = 2.4 \pm 0.7$) problems. Analysis also revealed a fitness × problem size interaction, [$F_{(1,\,38)} = 5.0$, $p = 0.04$, $\eta^2 = 0.12$]. *Post-hoc* analysis revealed that higher fit ($d = 2.7 \pm 0.5$) relative to lower fit ($d = 2.2 \pm 0.8$) children more accurately detected correct and incorrect solutions only for large size problems, [$t_{(38)} = 2.4$, $p = 0.02$].

ELECTROPHYSIOLOGICAL DATA

P1

Amplitude and latency data for the P1 component are presented in **Table 2**. Omnibus analysis of amplitude revealed a main effect of region, [$F_{(1,\,38)} = 13.72$, $p < 0.01$, $\eta^2 = 0.27$], which was superseded by a problem size × region interaction, [$F_{(1,\,38)} = 36.01$, $p < 0.01$, $\eta^2 = 0.49$]. Analysis also revealed a problem size × correctness interaction, [$F_{(1,\,38)} = 23.40$, $p < 0.01$, $\eta^2 = 0.38$], and correctness × region interaction, [$F_{(1,\,38)} = 7.21$, $p < 0.01$, $\eta^2 = 0.16$], which were superseded by a problem size × correctness × region interaction, [$F_{(1,\,38)} = 12.36$, $p < 0.01$, $\eta^2 = 0.25$]. *Post-hoc* analysis of the 3-way interaction revealed that P1 amplitude for all participants was greater during small-correct problems over the right ROI ($m = 9.2 \pm 7.6$) relative to the center ROI ($m = 6.2 \pm 4.6$), and during small-incorrect problems over the right ROI ($m = 9.7 \pm 8.2$) relative to the center ROI ($m = 6.5 \pm 4.8$). Further, amplitude during large problems was greater over the right ROI ($m = 8.0 \pm 4.6$) than the center ($m = 3.9 \pm 3.2$) and left ($m = 5.7 \pm 4.2$) ROIs, and amplitude was greater over the left ROI ($m = 5.7 \pm 4.2$) than the

Table 2 | Amplitude and latency data for the N170 and PI components for higher fit and lower fit children.

PI amplitude (μv)	**Higher fit**	**Lower fit**
Small-correct-left	8.0 (6.2)	11.2 (7.3)
Small-incorrect-left	8.4 (5.8)	12.1 (6.6)
Large-correct-left	7.7 (5.0)	8.2 (5.5)
Large-incorrect-left	7.1 (4.8)	8.3 (5.5)
Small-correct-center	4.6 (2.7)	8.0 (5.4)
Small-incorrect-center	4.6 (2.6)	6.6 (5.5)
Large-correct-center	3.0 (1.9)	5.5 (3.7)
Large-incorrect-center	2.2 (2.0)	5.1 (4.1)
Small-correct-right	7.5 (5.2)	8.9 (7.6)
Small-incorrect-right	10.4 (7.2)	14.2 (11.8)
Large-correct-right	10.5 (7.2)	10.5 (8.7)
Large-incorrect-right	9.7 (6.0)	10.3 (8.9)
P1 latency (ms)		
Small-correct-left	121.0 (20.3)	123.0 (17.0)
Small-incorrect-left	131.7 (19.2)	121.6 (19.3)
Large-correct-left	118.2 (18.7)	123.4 (16.4)
Large-incorrect-left	118.6 (18.4)	124.8 (16.5)
Small-correct-center	137.4 (22.1)	140.8 (22.1)
Small-incorrect-center	137.4 (23.8)	139.5 (17.0)
Large-correct-center	133.3 (19.3)	142.6 (19.6)
Large-incorrect-center	135.6 (29.3)	141.2 (27.7)
Small-correct-right	120.1 (18.9)	120.1 (18.9)
Small-incorrect-right	119.2 (16.6)	126.5 (21.5)
Large-correct-right	119.4 (21.2)	117.6 (18.9)
Large-incorrect-right	117.2 (23.4)	123.4 (21.1)
N170 amplitude (μv)		
Small-correct-left	−6.1 (6.3)	−3.7 (5.4)
Small-incorrect-left	−5.7 (6.9)	−2.9 (7.6)
Large-correct-left	−6.8 (4.9)	−4.5 (6.0)
Large-incorrect-left	−6.2 (4.1)	−3.5 (4.6)
Small-correct-center	−3.3 (4.6)	−2.3 (4.7)
Small-incorrect-center	−2.7 (4.5)	−2.3 (4.9)
Large-correct-center	−2.6 (2.8)	−2.1 (4.1)
Large-incorrect-center	−3.4 (2.7)	−2.3 (4.0)
Small-correct-right	−3.6 (4.5)	−0.4 (2.7)
Small-incorrect-right	−5.5 (5.5)	0.03 (6.5)
Large-correct-right	−5.4 (6.5)	−2.8 (3.8)
Large-incorrect-right	−5.4 (6.3)	−1.5 (4.0)
N170 latency (ms)		
Small-correct-left	195.7 (18.6)	193.6 (23.7)
Small-incorrect-left	193.4 (16.7)	192.1 (22.9)
Large-correct-left	200.8 (19.7)	200.1 (19.6)
Large-incorrect-left	200.1 (15.9)	197.9 (23.2)
Small-correct-center	201.8 (17.4)	202.8 (13.1)
Small-incorrect-center	198.8 (19.0)	200.5 (13.8)
Large-correct-center	201.5 (20.8)	204.9 (16.3)
Large-incorrect-center	208.2 (18.8)	206.4 (17.9)
Small-correct-right	198.5 (13.4)	198.4 (21.0)
Small-incorrect-right	196.1 (15.5)	201.6 (20.1)
Large-correct-right	200.0 (16.7)	194.7 (21.9)
Large-incorrect-right	202.9 (17.8)	195.2 (23.2)

μv, microvolts; ms, milliseconds.

center ROI ($m = 3.9 \pm 3.2$), [$t's_{(38)} \geq 2.65$, $p's \leq 0.01$]. In addition, amplitude during small-correct problems was greater ($m = 6.2 \pm 4.5$) than for large-correct problems ($m = 4.2 \pm 3.2$) over the center ROI, [$t_{(39)} = 3.03$, $p < 0.01$], and amplitude during small-incorrect problems was greater than large-incorrect problems over the left (small: $m = 7.7 \pm 5.1$; large: $m = 5.6 \pm 4.2$) and center (small: $m = 6.5 \pm 4.8$; large: $m = 3.5 \pm 3.6$) ROIs.

In addition, analysis revealed a fitness x correctness interaction, [$F_{(1,\ 38)} = 3.9$, $p = 0.05$, $\eta^2 = 0.09$], suggesting that lower relative to higher fit children exhibited larger P1 amplitude during incorrect problem solutions. However, *post-hoc* tests failed to reveal significant effects upon decomposition of the interaction, [$t's_{(38)} \leq 1.87$ $p's \geq 0.07$].

Analysis of latency revealed a main effect of region, [$F_{(1,\ 38)} = 18.78$, $p < 0.01$, $\eta^2 = 0.33$], which was superseded by a region × correctness interaction, [$F_{(1,\ 38)} = 32.64$, $p < 0.01$, $\eta^2 = 0.46$]. *Post-hoc* tests revealed longer latency over the center ROI, for correct and incorrect solutions (correct: $m = 138.5 \pm 19.2$; incorrect: $m = 138.4 \pm 20.7$), relative to the right (correct: $m = 119.1 \pm 15.4$; incorrect: $m = 121.8 \pm 17.3$) and left (correct: $m = 121.5 \pm 13.1$; incorrect: $m = 124.2 \pm 13.6$) ROIs, [$t's_{(39)} \geq 5.32$, $p's < 0.01$]. Analysis did not reveal any effect of fitness, [$F's_{(1,\ 38)} \leq 1.23$, $p's \geq 0.27$, $\eta's^2 \leq 0.03$].

N170

Amplitude and latency data for the N170 are presented in **Table 2**. Analysis of amplitude revealed a main effect of region, [$F_{(1,\ 38)} = 6.22$, $p = 0.02$, $\eta^2 = 0.14$]. *Post-hoc* analysis indicated that all participants demonstrated greater amplitude over the left ($m = -4.9 \pm 5.3$) relative to the center ($m = -2.6 \pm 3.8$) and right ($m = -3.1 \pm 4.8$) ROIs, [$t's_{(39)} \geq 2.5$ $p's < 0.02$]. Further, a main effect of fitness was revealed, [$F_{(1,\ 38)} = 5.63$, $p = 0.02$, $\eta^2 = 0.13$], which was superseded by a fitness × correctness interaction, [$F_{(1,\ 38)} = 4.61$, $p = 0.03$], $\eta^2 = 0.11$. *Post-hoc* tests revealed that higher fit ($m = -5.7 \pm 4.5$) relative to lower fit ($m = -1.9 \pm 4.3$) children demonstrated larger N170 amplitude only during incorrect problem verification, [$t_{(38)} = 2.66$, $p = 0.01$], while no such differences were observed for correct problem verification, [$t_{(38)} = 1.97$, $p = 0.06$]. No effects of fitness, problem size, correctness or region were observed for N170 latency, [$F's_{(1,\ 38)} \leq 1.09$, $p's \geq 0.30$].

P3

P3 amplitude and latency data are presented in **Table 3**. Analysis of amplitude revealed a main effect of problem size, [$F_{(1,\ 38)} = 15.30$, $p = 0.01$, $\eta^2 = 2.87$], which was superseded by a problem size × correctness × region interaction, [$F_{(1,\ 38)} = 5.23$, $p = 0.01$, $\eta^2 = 1.21$]. *Post-hoc* tests revealed that all participants demonstrated greater P3 amplitude over the right ROI during small problems ($m = 10.7 \pm 6.1$), relative to the left ($m = 7.5 \pm 4.5$) and center ($m = 7.3 \pm 4.3$), ROIs during large problems, [$t's_{(39)} \geq 3.52$], $p \leq 0.01$. Further, participants demonstrated greater P3 amplitude over the center ROI during small problems ($m = 9.3 \pm 5.4$) relative to large problems ($m = 7.3 \pm 4.3$), [$t_{(39)} = 3.52, p < 0.01$]. Further, a fitness × problem size interaction was observed, [$F_{(1,\ 38)} = 6.33, p = 0.02, \eta^2 = 0.14$]. *Post-hoc* tests revealed that higher fit children ($m = 8.1 \pm 2.8$) had smaller P3 amplitude relative to lower fit children ($m = 11.4 \pm 5.5$) during small problems, [$t_{(38)} = 2.36$], $p = 0.02$. Lastly, a fitness × correctness interaction indicated that lower fit ($m = 10.1 \pm 5.3$) relative to higher fit ($m = 7.3 \pm 2.7$) children exhibited larger P3 amplitude during incorrect problems, [$F_{(1,\ 38)} = 8.13$, $p = 0.002$, $\eta^2 = 0.17$]. However, *post-hoc* tests failed to decompose the interaction, [$t's_{(38)} \leq 2.16$, $p's \geq 0.04$].

Table 3 | Amplitude and latency data for the P3 and N400 components for higher fit and lower fit children.

P3 amplitude (µv)	**Higher fit**	**Lower fit**
Small-correct-left	7.2 (3.7)	10.7 (5.1)
Small-incorrect-left	6.5 (4.5)	12.5 (4.9)
Large-correct-left	7.8 (4.3)	8.1 (5.5)
Large-incorrect-left	6.4 (4.4)	7.8 (5.2)
Small-correct-center	8.4 (4.2)	9.9 (6.4)
Small-incorrect-center	7.7 (4.0)	11.0 (7.0)
Large-correct-center	7.5 (4.5)	7.9 (4.3)
Large-incorrect-center	6.4 (4.4)	7.3 (4.8)
Small-correct-right	9.9 (4.2)	11.4 (7.0)
Small-incorrect-right	8.7 (4.1)	11.0 (7.0)
Large-correct-right	8.4 (5.1)	8.7 (5.9)
Large-incorrect-right	7.9 (5.0)	9.5 (6.5)
P3 latency (ms)		
Small-correct-left	371.5 (71.1)	362.4 (57.8)
Small-incorrect-left	365.9 (76.6)	365.5 (45.3)
Large-correct-left	368.1 (71.6)	394.0 (48.0)
Large-incorrect-left	381.7 (41.6)	389.3 (71.9)
Small-correct-center	353.9 (56.8)	370.0 (68.4)
Small-incorrect-center	405.2 (87.8)	379.6 (60.0)
Large-correct-center	408.4 (68.0)	401.2 (62.7)
Large-incorrect-center	418.0 (79.4)	411.0 (69.0)
Small-correct-right	342.1 (55.2)	356.3 (63.0)
Small-incorrect-right	376.4 (83.0)	355.8 (51.6)
Large-correct-right	361.7 (58.3)	374.5 (60.5)
Large-incorrect-right	361.8 (74.4)	389.0 (74.3)
N400 amplitude (µv)		
Small-correct-left	2.0 (4.6)	5.3 (4.1)
Small-incorrect-left	0.1 (5.2)	5.3 (4.2)
Large-correct-left	2.2 (4.9)	4.0 (4.3)
Large-incorrect-left	−0.2 (4.1)	3.7 (4.5)
Small-correct-right	2.5 (5.4)	5.4 (6.0)
Small-incorrect-right	0.4 (4.6)	0.3 (6.5)
Large-correct-right	2.6 (3.8)	5.2 (3.8)
Large-incorrect-right	0.7 (4.8)	3.5 (5.2)
N400 latency (ms)		
Small-correct-left	387.7 (58.5)	374.6 (28.4)
Small-incorrect-left	392.0 (79.7)	375.7 (30.8)
Large-correct-left	399.9 (77.9)	378.8 (30.9)
Large-incorrect-left	399.4 (77.8)	377.9 (34.7)
Small-correct-right	396.9 (81.2)	380.6 (27.7)
Small-incorrect-right	390.4 (69.0)	381.7 (20.1)
Large-correct-right	390.6 (63.7)	374.4 (25.8)
Large-incorrect-right	404.7 (70.3)	377.8 (33.2)

µv, microvolts; ms, milliseconds.

P3 latency analyses revealed effects of problem size, [$F_{(1,\,38)} = 10.50$, $p < 0.01$, $\eta^2 = 0.28$], indicating that all participants demonstrated longer P3 latency during large ($m = 388.2 \pm 46.7$) relative to small ($m = 367.0 \pm 43.0$) problems. Analysis further revealed an effect of correctness, [$F_{(1,\,38)} = 3.96$, $p = 0.05$, $\eta^2 = 0.09$], indicating that participants had longer P3 latency during incorrect ($m = 383.2 \pm 48.7$) relative to correct ($m = 371.9 \pm 39.7$) problems. An effect of region was also observed, [$F_{(1,\,38)} = 5.98$, $p < 0.01$, $\eta^2 = 0.14$], indicating that P3 latency was longest over the center ROI ($m = 393.4 \pm 52.7$), and shortest over the right ROI ($m = 347.6 \pm 50.8$), with the left ROI ($m = 374.8 \pm 48.8$) falling in-between, [$t_{(39)} = 4.00$, $p < 0.01$]. Lastly, a fitness × size × correctness × region interaction was observed, [$F_{(1,\,38)} = 4.02$, $p = 0.02$, $\eta^2 = 0.1$], however, *post-hoc* tests failed to decompose the interaction, [$t'\mathrm{s}_{(38)} \leq 1.3$, $p'\mathrm{s} \geq 0.35$].

N400

N400 amplitude and latency data are presented in **Table 3**. Analysis revealed effects of fitness, [$F_{(1,\,38)} = 6.40$, $p = 0.02$, $\eta^2 = 0.14$], and correctness, [$F_{(1,\,38)} = 14.72$, $p < 0.01$, $\eta^2 = 0.28$], which were superseded by a fitness × correctness interaction, [$F_{(1,\,38)} = 8.25$, $p < 0.01$, $\eta^2 = 0.18$]. *Post-hoc* testing revealed that higher fit ($m = 0.2 \pm 0.9$) relative to lower fit ($m = 4.4 \pm 1.0$) children had larger N400 amplitude during incorrect problems, [$t_{(38)} = 2.96$, $p < 0.01$]. Analysis based on difference waves (incorrect-correct) confirmed this finding, revealing an effect of fitness, [$F_{(1,\,38)} = 8.25$, $p < 0.01$, $\eta^2 = 0.18$], indicating that higher fit children ($m = -2.1 \pm 2.0$) had greater N400 amplitude than lower fit children ($m = -0.3 \pm 1.8$) during incorrect solutions. No effects of fitness, problem size, ROI, or correctness were observed for N400 latency, [$F'\mathrm{s}_{(1,\,38)} \leq 2.29$, $p'\mathrm{s} \geq 0.14$, $\eta'\mathrm{s}^2 \leq 0.02$].

DISCUSSION

The aim of the current study was to extend the literature-base in cardiorespiratory fitness and cognition by assessing strategic, behavioral, and electrophysiological indices of arithmetic cognition in preadolescent children. Consistent with *a priori* predictions, higher fit children reported using retrieval strategies more often for large problems compared to lower fit children; however, all children reported relying more on retrieval strategies for small relative to large problems, suggesting that fitness has a selective relation with specific aspects of arithmetic cognition. Alternatively, no fitness differences were observed for standardized achievement. During the verification task, fitness primarily modulated performance for large problems, but all children demonstrated behavioral modulations as a function of problem size and solution correctness. On the electrophysiological level, both early and late components were modulated by fitness and all participants demonstrated modulations of multiple ERP components as a function of problem size and solution correctness. Thus, these findings extend the current knowledge base of aerobic fitness-related benefits during neurocognitive development and add to a growing body of research detailing the development of arithmetic cognition.

STRATEGY

Higher fit children reported greater use of retrieval strategies than their lower fit counterparts during large problem performance, revealing fitness-related differences in strategic deployment as a function of problem size. Beyond fitness, all children reported more frequent retrieval for small relative to large problems. Differences in arithmetic strategy selection are believed to reflect the underlying functional integration of higher-order neurocognitive functions such as memory, visuo-spatial ability, and cognitive control (Grabner et al., 2007; Wu et al., 2009); functions that are known to develop across childhood (Holmes et al., 2009; Luna, 2009; Dumontheil and Klingberg, 2012) and which are positively influenced by fitness (Chaddock et al., 2011; Pontifex et al., 2011; Hillman et al., 2012; Monti et al., 2012). Accordingly, the current data provide evidence to suggest that fitness may positively influence strategy selection during arithmetic performance by benefiting the underlying cognitive constructs necessary for mature strategic implementation. To the best of our knowledge, these are the first data to demonstrate shifts in arithmetic strategy as a function of fitness, and raise interesting questions regarding possible differential neural underpinnings sub-serving strategic implementation between higher- and lower-fit children.

ACHIEVEMENT

Contrary to our predictions and in opposition to previous research (California Department of Education, 2001, 2005; Castelli et al., 2007; Wittberg et al., 2012), no differences in achievement were observed as a function of fitness level. While perplexing, this result may be due to the fact that the current sample was comprised of relatively high math achievers, whom demonstrated both above average IQ and SES; factors known to mediate mathematical achievement (White, 1982; Sirin, 2005). It is also possible that differences in the sensitivity and specificity between standardized achievement tests employed in current and past research, may in part, account for this discrepancy. Further research is necessary to clarify the relation between fitness and performance on standardized tests of mathematical achievement.

While no effects were observed with respect to fitness, all children did perform better on the math concepts, relative to math computation, subsection of the KTEA-2. Conceptual arithmetic knowledge is a prerequisite for inferential and adaptive arithmetic expertise (Hatano, 1988; Domahs and Delazer, 2005), providing a fundamental understanding of arithmetic operations and principals (Domahs and Delazer, 2005). Computational knowledge, while building on conceptual knowledge, also requires procedural guidance of algorithm execution known as routine expertise (Hatano, 1988), as well as the retrieval of declarative facts (Ashcraft, 1987; Siegler, 1988; Campbell, 1995), which arises from a synergy of conceptual and procedural mathematical knowledge (Domahs and Delazer, 2005). As such, it is not surprising that 9–10 year old children demonstrated superior performance for conceptual relative to computation achievement, as the latter naturally develops upon conceptual foundations.

ARITHMETIC VERIFICATION PERFORMANCE

Comparison of d' scores between fitness groups revealed greater performance during large problems for higher- relative to lower-fit children. Furthermore, all children demonstrated decreased accuracy for large relative to small problems. Current explanations of the problem size effect attribute this phenomenon to differences in strategic deployment between large and small problems (Campbell and Xue, 2001; Zbrodoff and Logan, 2005), with less frequent and less efficient use of retrieval strategies for large relative to small problems. This results in greater interference between correct and incorrect solutions as problem sizes increase (Campbell and Xue, 2001; Campbell and Epp, 2004; Zbrodoff and Logan, 2005). As lower fit children reported relying on procedural strategies more frequently for large problems than their higher fit peers, lower fit children may have incurred a response criterion deficit, experiencing greater interference when attempting to detect correct and reject incorrect solutions. While novel to the arithmetic literature, differences in strategy implementation and interference control between higher- and lower-fit children is a common finding, with higher fit children regularly demonstrating more efficient and flexible strategy deployment, and superior interference control during experimental paradigms (Hillman et al., 2009; Pontifex et al., 2011; Voss et al., 2011; Chaddock et al., 2012). However, this is the first study to extend this finding to the domain of arithmetic. Thus, the beneficial influence of fitness on strategic deployment and interference control may confer neurocognitive benefits that translate across a variety of domains, including those necessary for arithmetic and academic success.

In addition, all children responded less accurately for incorrect relative to correct solutions, irrespective of problem size. Explanations for the split effect are less transpicuous than the problem size effect, as several plausible theories have been proposed (Campbell, 1987; Siegler, 1988; El Yagoubi et al., 2003; Duverne and Lemaire, 2005). Specifically, some researchers cite interference (Campbell, 1987), or frequency and strength of association between incorrect and correct solutions (Siegler, 1988), while others cite differences in verification strategy between correct and incorrect solutions (El Yagoubi et al., 2003; Duverne and Lemaire, 2005). Irrespective of cause, the current results provide information regarding the split effect during development, and more importantly, illustrate the interaction of the problem size and split effect (all children exhibited the poorest accuracy for large-incorrect problems). Accordingly, the current results provide an impetus for studying this interaction, particularly as the split and problem size effects, while well studied, are typically evaluated separately. Further evaluation of the combinatorial influence of the problem size and split effects will yield a finer understanding of arithmetic competency during development.

ERPs

Although no specific predictions were made relative to the early ERP components, several notable modulations as a function of fitness and task parameters occurred. First, while the P1 component is typically unevaluated in arithmetic verification paradigms, the current results suggest that fitness, solution correctness, and problem size may modulate P1 amplitude in children (see **Figures 2–4**). Specifically, although fitness significantly interacted with solution correctness, subsidiary analyses failed to decompose into significant differences among the groups. However, the moderate effect sizes across ROIs ($0.68 > d > 0.30$) suggest significant effects may emerge in a larger sample (see **Figure 3**). Furthermore, children in the current study exhibited greater P1 amplitude during small relative to large solutions, and for incorrect relative to correct solutions. While P1 amplitude modulations as a function of solution size may be attributed to differing physical properties or spatial distributions of attention between small (e.g., 9) and large (e.g., 17; Mangun and Hillyard, 1991; Luck et al., 1994; Muluh et al., 2011) solutions, neither physical properties nor attentional distribution can account for amplitude modulations as a function of solution correctness (see **Figure 2**). As such, further research appears necessary to elucidate the meaning and theoretical implications of P1 amplitude modulations during arithmetic verification in relation to fitness and task parameters.

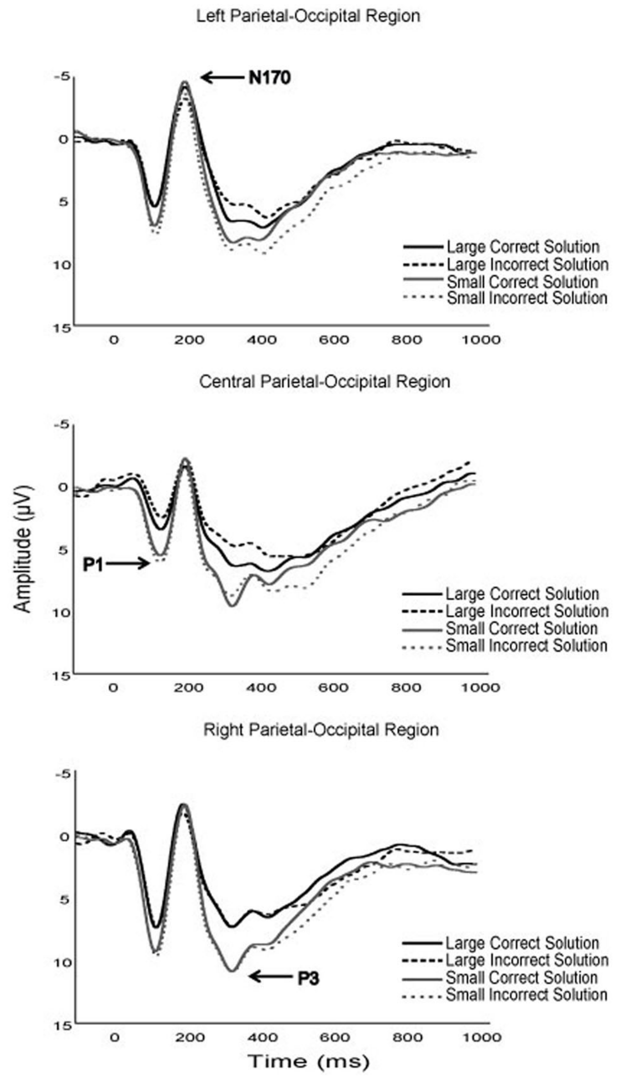

FIGURE 2 | Grand average waveforms of the P1, N170, and P3 components for all participants, for all task experimental task solution conditions.

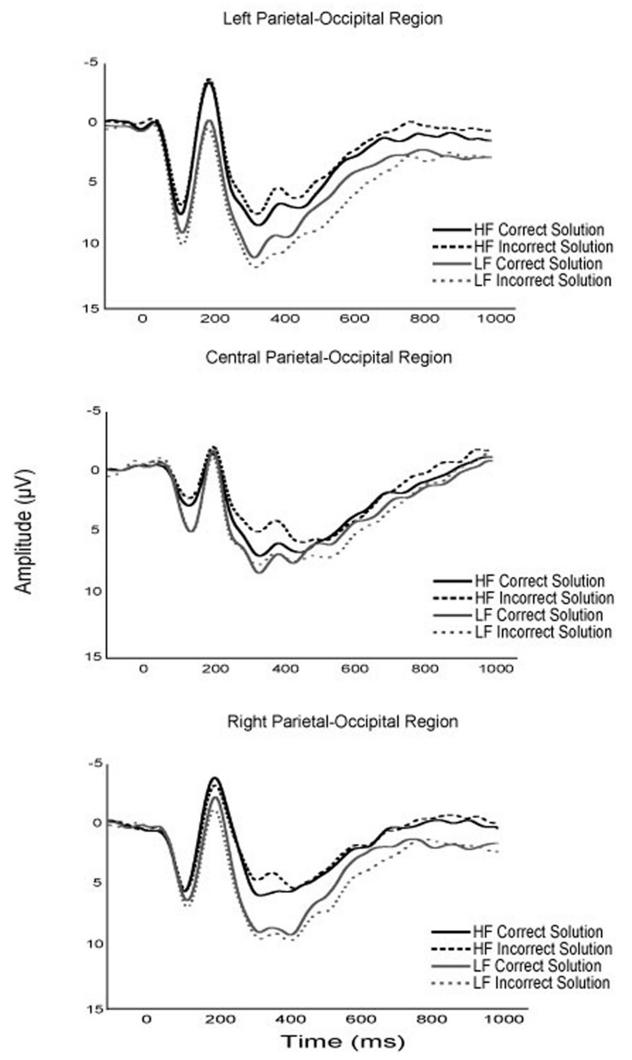

FIGURE 3 | Grand average waveforms of the P1, N170, and P3 components for higher and lower fit participants, for correct and incorrect experimental task solutions.

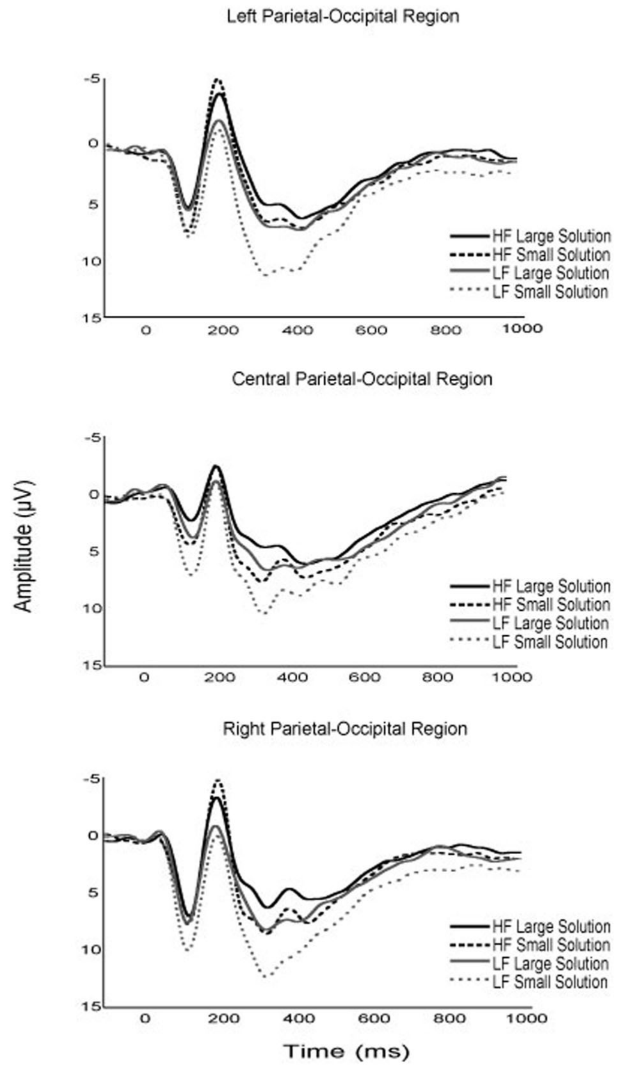

FIGURE 4 | Grand average waveforms of the P1, N170 and P3 components for higher and lower fit participants, for large and small experimental task solutions.

Secondly, higher fit children demonstrated greater N170 amplitude than their lower fit peers, and this group difference was found to interact with solution correctness, such that higher fit children demonstrated the greatest amplitude difference during incorrect solution processing (see **Figure 3**). The left lateralization of the N170 across participants observed herein links this component to the parietal-occipital N170 believed to reflect experience-dependent changes in visual expertise (Gauthier et al., 2003; Schlaggar and McCandliss, 2007; Maurer et al., 2008). Within the context of arithmetic verification, it has been suggested that the N170 reflects numeric symbol encoding (He et al., 2011). As such, the N170 observed during arithmetic verification may be an index of experience-dependent expertise in numeric symbol encoding. Fitness thus appears to benefit the neural resources responsible for numeric symbol encoding, with a disproportionate benefit for encoding incorrect solutions. *Post-hoc* explanations of these data suggest that fitness may expedite the maturation of arithmetic expertise by facilitating differential numeric encoding of correct and incorrect solutions.

Both animal (van Praag et al., 1999; Cotman and Berchtold, 2002, 2007; van Praag, 2008) and human (Colcombe and Kramer, 2003; Kramer and Erickson, 2007; Chaddock et al., 2011; Erickson et al., 2011; Voss et al., 2011; Monti et al., 2012; Chaddock-Heyman et al., 2013) studies demonstrate the beneficial effects of cardiorespiratory fitness on experience-dependent changes in plasticity, connectivity, and integrity of a variety of cortical and subcortical areas. Furthermore, neural structures and networks critical for arithmetic cognition, such as the hippocampus (Rivera et al., 2005; Cho et al., 2011; De Smedt et al., 2011), prefrontal and posterior parietal cortices (Dehaene et al., 2003; Nieder and Dehaene, 2009; Cho et al., 2011; De Smedt et al., 2011), and the fronto-parietal network (Dehaene et al., 2003; Nieder and

Dehaene, 2009), show disproportionate fitness-related benefits (Colcombe and Kramer, 2003; Colcombe et al., 2004a,b; Hillman et al., 2008; Erickson and Kramer, 2009; Chaddock et al., 2011; Erickson et al., 2011; Voss et al., 2011). Therefore, fitness may facilitate experience-dependent changes in the neural architecture sub-serving numeric symbol encoding, resulting in the functional electrophysiological alterations currently observed. Future multimodal research will be well positioned to further elucidate the neural specificity of this relation during arithmetic performance.

With respect to later ERP components, lower- relative to higher-fit children exhibited greater P3 amplitude during small problem solutions, with the greatest difference occurring for small-incorrect solutions (see **Figures 3**, **4**). While all participants exhibited greater P3 amplitude for small relative to large problems, the current fitness finding suggests that small problems, required greater attentional resources for lower- relative to higher-fit children. Stated differently, higher fit children were able to maintain equivalent performance for small problems, irrespective of solution correctness, while up-regulating fewer attentional resources relative to their lower fit peers. The current results add to those of Wu and Hillman (2013), and provide further evidence that pediatric fitness is associated with more flexible attentional resource allocation in relation to task demands. Further evidence is provided by research examining pediatric fitness and brain function on the hemodynamic level (Chaddock et al., 2012; Chaddock-Heyman et al., 2013), which demonstrate that higher fit children exhibit more efficient neural resource allocation in relation to task demands during a task requiring attentional inhibition and interference control. Given, the variety of tasks (i.e., attentional blink, arithmetic verification, flanker) and multimodal (ERP, fMRI) convergence, it appears that higher fit children may derive a generalizable benefit across tasks through optimizing attentional resource allocation in relation to task demands.

In addition to P3 amplitude modulations, higher fit children exhibited significantly greater N400 amplitude to incorrect solutions relative to their lower fit counterparts; a finding further confirmed by difference wave analysis (see **Figure 5**). Accordingly, fitness appears to influence semantic memory processing during arithmetic verification. Further, tertiary analysis revealed that d' scores were positively correlated with N400 amplitude, suggesting that fitness may facilitate the detection of correct solutions and rejection of incorrect solutions via differential activation of semantic memory networks. Indeed, the only other study to evaluate the underlying neurocognitive processes giving rise to greater achievement scores in higher fit children observed a similar finding within the domain of linguistic performance (Scudder et al., 2014). In this study, behavioral and electrophysiological function in higher- and lower-fit children was observed as they read sentences that were either semantically or syntactically congruent (correct) or incongruent (incorrect). In addition to exhibiting shorter RT, higher- relative to lower-fit children exhibited greater N400 amplitude and shorter N400 latency; suggesting that cardiorespiratory fitness during development facilitates the extraction of semantic information during sentence reading. Thus, the current results both compliment and extend the results of Scudder et al. (2014), which together suggest that fitness positively relates to semantic processing during academic-based tasks. The N400 therefore appears to be a convergent electrophysiological mechanism supporting fitness-related benefits observed across academic domains.

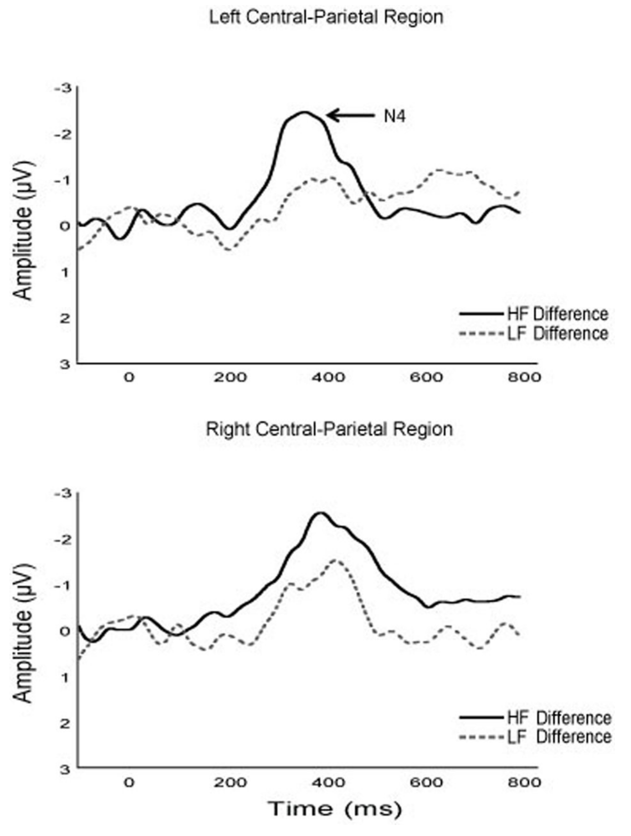

FIGURE 5 | Grand average difference waveforms of the N400 component for higher and lower fit participants.

LIMITATIONS AND CONCLUSION

While the comprehensive nature of the current study yields valuable information regarding the relation of cardiorespiratory fitness to aspects of arithmetic cognition, it is not without limitations. First, the study design was cross-sectional in nature and it is always possible that some unmeasured variable may have influenced the current results. However, demographic variables such as age, IQ, SES and pubertal timing did not differ between groups and were relatively homogenous between participants. In addition, the relatively small sample size may limit the interpretable power of the current results. Future longitudinal studies with greater sample size will help determine the robustness of the observed effects. Lastly, the current sample was relatively high performing in terms of IQ and academic achievement, potentially limiting the generalizability of the current results.

Irrespective of limitations, the findings observed herein add important information to the fitness-cognition literature by revealing that the beneficial effects of fitness extend on the behavioral and neural levels to the domain of arithmetic cognition. The current results provide further incentive for promoting physical activity and fitness in youth, while engendering further inquiry into the relation of fitness and scholastic development. By further detailing strategic, behavioral, and electrophysiological indices of arithmetic cognition during development, the current results also call for a more refined examination of arithmetic development through the evaluation of early ERP components during arithmetic verification as well as the interaction of size and split effects. In summary, the current results add important information to the exercise and arithmetic cognition literatures, illustrating the importance of a physically active lifestyle as well as comprehensive experimental designs when evaluating scholastic development. Lastly, the current results further emphasize the importance of cardiorespiratory fitness during childhood not only for cardiovascular health, but also for neurocognitive and scholastic development.

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Higher levels of cardiovascular fitness are associated with better executive function and prefrontal oxygenation in younger and older women

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Aim: Many studies have suggested that physical exercise training improves cognition and more selectively executive functions. There is a growing interest to clarify the neurophysiological mechanisms that underlie this effect. The aim of the current study was to evaluate the neurophysiological changes in cerebral oxygenation associated with physical fitness level and executive functions.

Method: In this study, 22 younger and 36 older women underwent a maximal graded continuous test (i.e., $\dot{V}O_{2max}$) in order to classify them into a fitness group (higher vs. lower fit). All participants completed neuropsychological paper and pencil testing and a computerized Stroop task (which contained executive and non-executive conditions) in which the change in prefrontal cortex oxygenation was evaluated with near infrared spectroscopy (NIRS).

Results: Our findings revealed a Fitness × Condition interaction ($p < 0.05$) such that higher fit women scored better on measures of executive functions than lower fit women. In comparison to lower fit women, higher fit women had faster reaction times in the Executive condition of the computerized Stroop task. No significant effect was observed in the non-executive condition of the test and no interactions were found with age. In measures of cerebral oxygenation (ΔHbT and ΔHbO_2), we found a main effect of fitness on cerebral oxygenation during the Stroop task such that only high fit women demonstrated a significant increase in the right inferior frontal gyrus.

Discussion/Conclusion: Higher fit individuals who demonstrate better cardiorespiratory functions (as measured by $\dot{V}O_{2max}$) show faster reaction times and greater cerebral oxygenation in the right inferior frontal gyrus than women with lower fitness levels. The lack of interaction with age, suggests that good cardiorespiratory functions can have a positive impact on cognition, regardless of age.

Keywords: fitness, stroop, executive function, cerebral oxygenation, prefrontal cortex, right inferior frontal gyrus

INTRODUCTION

Several studies have demonstrated that the aging process is accompanied by a decline in numerous cognitive domains (Drag and Bieliauskas, 2010; Salthouse, 2010). Among cognitive processes, executive functions and attentional control are particularly sensitive to aging (McDowd and Shaw, 2000). Executive functions generally refer to "higher-level" functions (planning, inhibiting, switching) involved in the control and regulation of cognitive processes (Miyake et al., 2000). Several neuroimaging studies have supported that executive functions such as inhibition and switching are under control of the frontal and prefrontal cortex (see reviews: Fuster, 2000; Turner and Spreng, 2012). The age-related deterioration of these abilities has often been associated with substantial anatomical and physiological changes (Bishop et al., 2010) and particularly in the frontal areas of the cerebral cortex (Yuki et al., 2012). However, it has also been suggested that aged-related brain atrophy and age-associated neurophysiological changes can be reduced with regular physical activity (Yuki et al., 2012).

Currently, it is recognized that regular physical activity is the best strategy (Deweerdt, 2011) to promote general health (physical and cognitive). Several studies have supported a delay in cognitive decline in physically active individuals (Angevaren et al., 2008). Several reviews on cardiovascular fitness and neurocognitive functions in older adults (Spirduso, 1980; McAuley et al., 2004) suggests "that maintaining higher levels of aerobic fitness may protect the brain against the normal effects of aging as well as cumulative effects of age-associated health problems" (McAuley et al., 2004, p. 218) but also proposes that more research is needed to clarify the underlying mechanisms of these changes in humans. Intervention studies also tend to support the notion that physical activity can reduce cognitive decline and lead to cognitive improvement in older adults. These studies suggest that aerobic fitness training is an effective way to enhance cognition in older adults and more selectively the executive functions of older adults, which are at particular risk for decline with age. Indeed, the results of the Colcombe and Kramer (2003) meta-analysis support improvements in several cognitive domains after aerobic training but these effects were greatest in the executive function domain. These results are further supported by current fitness level and intervention research (Boucard et al., 2012; Predovan et al., 2012). In their cross-sectional study, Boucard et al. (2012) demonstrated that physical fitness was selectively associated with better inhibitory control. Furthermore, Predovan et al. (2012) observed, that in comparison to wait-list controls, individuals who completed 3 months of aerobic training showed significant improvements in the Executive (inhibition/switch) condition of the Stroop task. In addition, only the trained group demonstrated a significant correlation between this executive measure and fitness level ($\dot{V}O_{2max}$ estimate).

One shortcoming of many of the studies that examine the impact of physical fitness on cognitive performances is that physical fitness is often measured by self-reported questionnaires or submaximal tests. The types of questionnaires used are typically not adapted to older populations and are sensitive to social desirability, leading to an overestimation of the fitness level in older adults. Since older adults are often more sedentary than younger adults, this may increase the chance that a self-reported active older person would in fact be more sedentary than a self-reported sedentary younger adult. The gold standard index of physical fitness and cardiorespiratory health is $\dot{V}O_{2max}$, which can be evaluated during a maximal graded exercise test using a computerized indirect calorimetric system. Physical fitness level calculated with the $\dot{V}O_{2max}$ correlate with global cognitive function (Brown et al., 2010; Davenport et al., 2012; however see Etnier et al., 2006 for exception), which suggests that using $\dot{V}O_{2max}$ is an important methodological choice when evaluating the associations between fitness level and cognitive function.

Given that there have been studies that have demonstrated a selective effect of fitness level on cognitive performance (Hall et al., 2001; Colcombe and Kramer, 2003; Bherer et al., 2013; Guiney and Machado, 2013) a growing body of literature has focused on understanding how physical training enhances cognitive performance. The preliminary research on this topic has fostered the development of theoretical models that assess and attempt to identify the neurophysiological pathways by which physical training enhances cognitive function. Several anatomical and neurophysiological parameters seem to be associated with improvement in executive performance in healthy fit subjects. Several studies demonstrate that regular physical training influences brain plasticity and increases the gray (Colcombe et al., 2003, 2004; Weinstein et al., 2012; Yuki et al., 2012) and white matter volume (Colcombe et al., 2003; Johnson et al., 2012; Tseng et al., 2013) in the brain, as well as an increase in the hippocampal volume (Erickson et al., 2009; Chaddock et al., 2010; Erickson et al., 2011; Szabo et al., 2011). Recently, Weinstein et al. (2012) reported that older subjects with a higher $\dot{V}O_{2max}$ demonstrated better executive performance in the Stroop task and that this was associated with a greater prefrontal cortex volume. In line with animal studies on this topic, factors such as brain derived neurotrophic factors (BDNF) serve to promote neurogenesis, angiogenesis and synaptogenesis, most likely supporting the improvement in cognition (Cotman et al., 2007; Davenport et al., 2012). However, additional research is needed to support this hypothesis in humans.

Furthermore, other neurophysiological mechanisms could explain the relationship between cardiorespiratory fitness and cognitive function. Processing in the brain, including the cognitive processing is critically dependent on adequate blood flow to respond the energy and oxygen needs of the tissue, and this is mediated by the cerebral vasculature of the individual. Regular physical exercise is a powerful stimulus to improve vascular health and cerebral blood flow (Ainslie et al., 2008; DeVan and Seals, 2012). The positive relationship between cerebrovascular health and cardiorespiratory fitness is supported by evidence of angiogenesis and change in endothelial function (Bolduc et al., 2013), mediated by the liberation of BDNF and vascular growth factor (VEGF). Based on the preceding evidence this positive relationship between cardiorespiratory health and cognition could be mediated by vascular mechanisms (Davenport et al., 2012), such as cerebrovascular reserve, improving oxygen transport and delivery to the cerebral cortex.

Cerebral oxygenation seems to play an important role in regulation of cognitive processes. The availability of oxygen content in the brain seems to regulate positively or negatively cognitive processing. For Example, during hypoxia, when there is a lack of oxygen available to the brain, cognitive performance is poorer (Lieberman et al., 1994) and after glucose supplementation, which improves the cerebral oxygenation, cognitive performance is enhanced (Gagnon et al., 2012). In normal aging, in the absence of major neurological events, it's well known that aging is accompanied by a lower baseline cerebral blood flow (Bangen et al., 2009) and lower cerebral oxygenation (Mehagnoul-Schipper et al., 2002; Fisher et al., 2013). From a clinical standpoint, reduced cerebrovascular health can be linked to cognitive decline in older adults. During the aging process, the hypoperfusion (decrease in perfusion) can lead to cognitive impairment and increase the risk of developing neurological disorders and stroke (Bangen et al., 2009). Based on this evidence, it seems plausible that poor cardiovascular health and reduced cerebrovascular function may result in poor cognitive performance. Emerging neuroimaging technologies such as near infra-red spectroscopy (NIRS-optical imaging) provide a good measure of cerebrovascular health in aging adults (Suhr and Chelberg, 2013) and permit further investigation of the role of cerebral oxygenation in cognitive processing of higher fit individuals. Indeed, optical imaging is a promising tool to study neurovascular coupling and could be used to complement existing cognitive neuroscience data (Fabiani et al., 2014).

Although several animal studies have shown that physical training can improve angiogenesis and enhance the O_2 transport in the brain (see reviews Davenport et al., 2012, p. 157; Bolduc et al., 2013) there are a limited number of studies that have evaluated the cerebral oxygenation in higher fit people. To the best of our knowledge, only two studies showed a positive effect of physical fitness on cerebral oxygenation. In a sample of patients with heart failure, Fu et al. (2013) observed an improvement on cerebral oxygenation during maximal exercise after an aerobic training program. Furthermore, Fabiani et al. (2014), observed a greater response in cerebral oxygenation during a visual task in higher fit people than sedentary control older subjects. To date, no study has evaluated the association between of physical fitness and cerebral oxygenation during a cognitive task in younger and older adults.

Taken together, existing evidence suggests a positive relationship between high levels of fitness and high levels of executive performance that may be related to cerebral oxygenation. However, to our knowledge, no study has examined all three of these factors in a sample of fit younger and older adults. Therefore, the current study was designed to assess fitness level, cerebral oxygenation changes and cognitive performances in young and old people, in order to explore if fitness level is associated with executive control in a Stroop task. In addition, we separated our sample into younger and older adults in order to explore if increasing age influenced the relationship between fitness level, executive control, and cerebral oxygenation. We hypothetized that within our sample, those that were more physically fit would perform better on the Stroop task and demonstrate better performances in the executive condition of the Stroop task, than individuals with lower physical fitness levels and that this difference would be related to increased cerebral oxygenation during the task in the higher fit individuals in comparison to the lower fit.

METHOD

PARTICIPANTS

Twenty-two young (age: 24.6 ± 3.6, range [19–34]) women and 36 old women (age: 62.9 ± 5.4, range [55–72]) participated in this study. All participants signed a written statement of informed consent. They were non-smokers, did not undergo major surgery 6 months prior to the experiment, did not report any neurological or psychiatric disorders and were not taking medication known to affect cognition. To exclude individuals with signs of dementia or depression, older participants completed the Mini-Mental State Examination (scores ranged between 26 and 30, Folstein et al., 1975), and the Geriatric Depression Scale (scores above 11 excluded). The younger participants completed the Beck Depression Inventory. Participants were screened for perceptual impairment by completing a questionnaire on auditory and visual function. Moreover, given the physical implications of the study, participants were also screened and excluded for cardiovascular disease, vascular peripheral attacks and moderate to severe hypertension based on self-report. The protocol was reviewed and approved by the Research Ethics Board of the Research Center of the Geriatrics Institute of Montreal (Canada), and has been conducted in accordance with recognized ethical standards and national/international laws.

STUDY DESIGN

All participants completed a cardiorespiratory and a cognitive assessment over a 3-week period. During the first session participants signed the consent form and completed questionnaires on health and mental status. During the second session, participants completed the aerobic test and the clinical neuropsychological tests. Cerebral oxygenation was measured during the computerized Stroop task in a third session.

AEROBIC FITNESS ASSESSMENT

The maximal continuous graded exercise test was performed on cycle ergometer (Lode). Oxygen uptake ($\dot{V}O_2$) was determined continuously on a 15-s basis using an automated cardiopulmonary exercise system (Moxus, AEI Technologies, Naperville, IL, USA). Gas analyzers (S3A and CD3A, AEI Technologies, Naperville, IL, USA) were calibrated before each test, using a gas mixture of known concentration (15% O_2 and 5% CO_2) and ambient air. Their accuracy was ± 0.003% for oxygen and ± 0.02% for carbon dioxide (data provided by the manufacturer). The turbine was calibrated before each test using a motorized syringe (Vacu-Med, Ventura, CA, USA) with an accuracy of ± 1%. The tidal volume was set at 3 l.

Initial workload was set at 0.75 or 1 W per kilogram (kg) of body weight according to the participant's physical activity level and increased by 15 W every minute until voluntary exhaustion. Strong verbal encouragement was given throughout the test. The highest $\dot{V}O_2$ over a 15-s period during the test was considered as maximal oxygen consumption ($\dot{V}O_{2max}$, in $ml.kg^{-1}.\ min^{-1}$). To ensure patient security, electro-cardiographic activity was monitored continuously using a 12-lead ECG (Marquette, Missouri) and blood pressure was measured manually every 2 min using a sphygmomanometer. According recommendations made by Duncan et al. (1997) and Midgley et al. (2007), $\dot{V}O_{2max}$ was defined when two of three criteria were satisfied: (1) a plateau in $\dot{V}O_2$, (2) a heart rate > 90% or equivalent to their age predicted maximum (i.e., 220—age) and (3) a respiratory exchange ratio >1.1. Aerobic fitness group assignments (i.e., higher fit and lower fit) were based on age- and gender-referenced $\dot{V}O_{2max}$ norms (Shvartz and Reibold, 1990). Subjects were considered "higher fit" when their $\dot{V}O_{2max}$ correspond to the fitness level of categories 1-3 [excellent to good], and "lower fit" in categories 4–7 [average to very poor] (Labelle et al., 2013).

COGNITIVE ASSESSMENT

Neuropsychological tests

Psychomotor speed was measured with the Digit Symbol Substitution Test (DSST, WAIS-III, Wechsler, 1997). In this test, the participant had to associate symbols to numbers (1–9) by referring to a response key consisting of rectangles containing a number in the top part and a symbol in the bottom part. The participant had 120 s to draw as many symbols as possible.

The Trail Making test and the Modified Stroop color test (Bohnen et al., 1992, adapted in French) were used to assess attention and executive functions. In the Trail Making Test part A, the participant had to draw a line joining numbers (from 1 to 25) as fast as possible. In Part B, the participant had to draw a line alternating between letters in alphabetical order and numbers in ascending order (1-A-2-B-3-C, etc.) as fast as possible. The dependent variables are the time to complete each part. The paper and pencil, Modified Stroop color test includes four conditions and provides a measure of inhibition and mental flexibility. In the reading condition, the participant had to read aloud color words as fast as possible. In the naming condition she had to name the color of rectangles. In the interference condition, color-words were printed in a color that differs from their meaning (e.g., red printed in green) and the task was to name the color of the word (green in the example) and avoid reading the word. In the flexibility condition, the participant had to alternate between naming the color of the color-words, and reading the words (when the color-words appear in a square). In all conditions, words list were printed on a sheet of paper and participants had to provide their answer verbally as fast as possible. Dependent variables were the time to complete each condition and the number of errors committed (%).

Computerized Stroop task

The Computerized Modified Stroop task was based on the Modified Stroop Color Test (Bohnen et al., 1992) and included two experimental conditions: Naming and Executive. Each block lasted 60 s, and was interspersed with 60-s resting blocks. Overall, there were four experimental task blocks (2 naming and 2 executive) and 5 resting blocks, for a total length of 9 min. All trials began with a fixation cross for 1.5 s, and all visual stimuli appeared in the center of the computer screen for 2.5 s. Participants provided their responses with two fingers of their right hand on a QWERTY keyboard. In the Naming block, participants were presented with a visual stimulus (XXXX) colored in green or in blue and participants were asked to identify the color of the ink with a button press. In the Executive block, each stimulus consisted of a color-word (BLUE or GREEN) printed in the incongruent ink color (i.e., the word BLUE was presented in green ink). Participants were asked to identify the color of the ink (i.e., green). In one third of the trials of the Executive block, a large rectangle appeared around the word. When this occurred, participants were instructed to read the word instead of identify the color of the ink (i.e., BLUE). As such, within the Executive block, there were both inhibition trials in which the participant had to inhibit their reading of the word and correctly identify the color of the ink and there were switch trials in which the participant had to switch their response mode to reading the word and not identifying the color of the ink when a rectangle appeared around the word presented. In total, there were 30 Naming trials and 30 Executive trials (20 inhibition and 10 switch trials). These two blocks of the computerized Stroop task are presented in the **Figure 1**. A practice session was completed before the acquisition run. The practice consisted of a shorter version of the task and included visual feedback when participants produced incorrect responses. Dependent variables were reaction times and the number of errors committed (%).

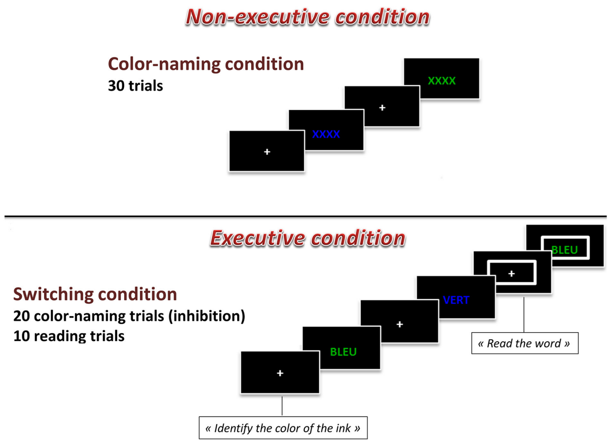

FIGURE 1 | Graphical representation of the computerized Stroop task.

CEREBRAL OXYGENATION

Changes in concentration of oxyhemoglobin (HbO_2) and deoxyhemoglobin (HbR) were measured by a multichannel, continuous-wave spectrometer (CW6, TechEn Inc., Milford, MA), using an 830 nm wavelength that is more sensitive to HbO_2 and a 690 nm more sensitive to HbR. Combining the multispectral measurements with known extinction coefficients of hemoglobin, concentration changes of HbO_2 was calculated using the modified Beer-Lambert and a path-length factor of 5.93. As illustrated in **Figure 2**, two arrays of 4 sources and 8 detectors were mounted on plastic helmets covering prefrontal regions. Two probes (one on each hemisphere) were arranged with one central, anterior-posterior row of four emitters per hemisphere. Sixteen detectors were placed strategically 2.8 cm away from the emitters, eight of them were dorsal, while the other eight were ventral, so that each probe had four dorsal detectors and for ventral detectors. The two probes were placed symmetrically over the lateral prefrontal cortex and the most anterior and most ventral pair of emitter-detector of each probe was placed on Fp1/Fp2 using the 10/20 system. Fp1 and Fp2 regions have been found to correspond to the superior and medial frontal gyri (Okamoto et al., 2004). This method and setup has already been used successfully in our previous research projects (Gagnon et al., 2012; Lague-Beauvais et al., 2012). The 14 source–detector pairs were combined into four different approximate regions of interests (ROI) that do not refer exactly to the underlying brain regions. They consisted of pairs 1–4 for the anterior DLPFC (BAs 9, 10 and 46), 5–7 for the posterior DLPFC (BAs 6 and 4), 8–10 for the anterior VLPFC (BAs 10, 45 and 46) and 11–14 for the posterior VLPFC (BAs 4, 6, and 44) for both hemispheres (**Figure 1**). The illustration of the brain mapping imaging is represented in **Figure 3**. The NIRS transmitters were tightly secured with a tensor bandage

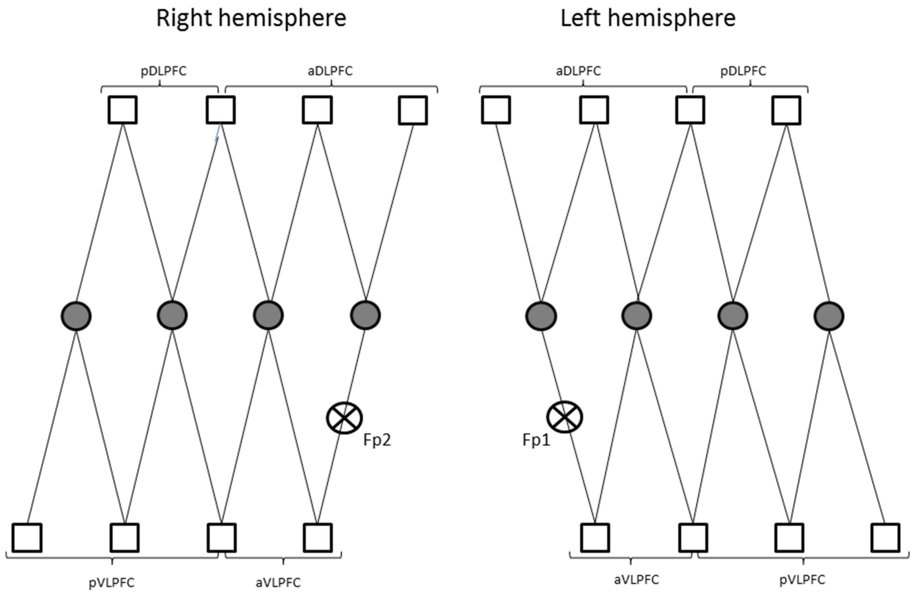

FIGURE 2 | Representations of the two arrays of 4 sources (circle) and 8 detectors (square) on plastic helmets covering prefrontal regions. (pDLPFC, posterior dorsolateral prefrontal cortex; aDLPFC, anterior dorsolateral prefrontal; pVLPFC, posterior ventrolateral prefrontal cortex; aVLPFC, anterior ventrolateral prefrontal cortex; Fp1/Fp2, frontal mark according the 10/20 system; see Okamoto et al., 2004).

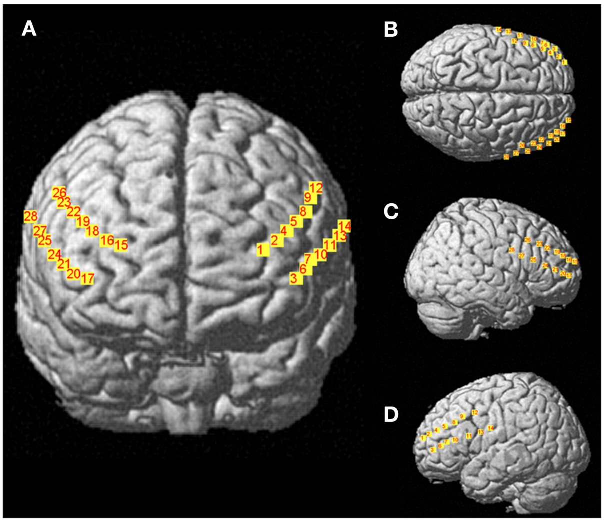

FIGURE 3 | Representations of 28 channels NIRS (i.e., detectors-sources) covering prefrontal regions (A), Frontal view; (B), Top view; (C), right sagittal view; (D), left sagittal view.

wrapped around the forehead, taking sufficient care to ensure that there was no interference of background light and to limit movement during cognitive task. Variables of interest were relative changes in concentration of ΔHbO$_2$, ΔHbr, and ΔHbT compared to the baseline (1 min at rest before the computerized Stroop task) (Gagnon et al., 2012; Lague-Beauvais et al., 2012), because continuous-wave technology does not allow quantifying absolute concentration due to the incapacity of measuring optical path lengths (Delpy and Cope, 1997; Hoshi, 2003; Ferrari and Quaresima, 2012).

ANALYSIS OF NIRS SIGNAL

NIRS data analysis was performed in Matlab (The MathWorks, Natick, MA) using the nirs10 toolbox (Pouliot et al., 2012) based on SPM and NIRS_SPM (Ye et al., 2009) with additional modules for ANOVAs. A principal component analysis was done to remove the 6 largest components from the data (Peng et al., 2014). A Butterworth order 2 high pass filter at 0.0042 Hz and a low pass filter with the shape of the SPM8 canonical hemodynamic response function (HRF) were applied. The analysis of NIRS signal was performed by block (i.e., by condition, including all trials), without separating out errors trials. A general linear model (GLM) was estimated for each NIRS channel and for each patient using this same HRF for each chromophore (HbO$_2$, HbR, and HbT). The results were interpolated onto left, right and frontal 2-dimensional maps (Ye et al., 2009), assuming identical NIRS source and detector positions for all subjects.

STATISTICAL ANALYSES

Standard statistical methods were used for the calculation of means and standard deviations. Normal Gaussian distribution of the data was verified by the Shapiro–Wilks test and homoscedasticity by a modified Levene Test. The compound symmetry, or sphericity, was checked by the Mauchley test. When the assumption of sphericity was not met, the significance of F-ratios was adjusted according to the Greenhouse–Geisser procedure when the epsilon correction factor was <0.75, or according to the Huyn–Feld procedure when the Epsilon correction factor was

>0.75. An analysis of variance (Age x Fitness x Measures) was performed. For the NIRS data, a mixed Two-Way ANOVA (fitness by condition) was estimated pixel wise on the interpolated maps and corrected for multiple comparisons using the Euler characteristic methodology (Li et al., 2012). For Trail test, Stroop test (paper pencil and computerized version), we performed an ANOVA (Age × Fitness × Condition). A *post-hoc* multiple comparisons Bonferroni test was performed. The magnitude of the difference was assessed by the Effect Size (ES), as presented elsewhere (Dupuy et al., 2010). The magnitude of the difference was considered either small ($0.2 < ES < 0.5$), moderate ($0.5 < ES < 0.8$), or large ($ES > 0.8$) (Cohen, 1988). The significance level was set at $p < 0.05$ for all analyses.

RESULTS

Concerning the paper and pencil neuropsychological tests, the ANOVA showed a main effect of age on the substitution test [$F_{(3, 54)} = 30.06$, $p < 0.01$], on the similarities test $F_{(3, 54)} = 4.50$, $p < 0.05$, on the Stroop task [$F_{(1, 54)} = 8.57$, $p < 0.01$] and on the Trail Making test [$F_{(1, 54)} = 15.96$, $p < 0.01$]. We found also a condition × age interaction for the Stroop task [$F_{(1, 54)} = 4.78$, $p < 0.05$] and for the Trail Making test [$F_{(1, 54)} = 8.41$, $p < 0.01$]. We also found a main effect of age [$F_{(1, 54)} = 53.0$, $p < 0.001$] and fitness [$F_{(1, 54)} = 19.0$, $p < 0.001$] on $\dot{V}O_{2max}$. All these results are presented in **Table 1**. There was no main effect of fitness on any of the paper and pencil neuropsychological tests. Concerning the reaction times in the computerized Stroop task, the ANOVA revealed a main effect of condition [$F_{(1, 54)} = 342.8$, $p < 0.05$], a Condition x Fitness interaction [$F_{(1, 54)} = 5.6$, $p < 0.05$] and a Condition × Age interaction [$F_{(1, 54)} = 13.7$, $p < 0.05$]. The condition × Fitness × Age interaction was non-significant. These results are presented in **Figure 4** and **Table 2**. There was no main effect of fitness or age difference in the number of errors produced.

Concerning the NIRS data, the ANOVA indicated main effect of Fitness. *Post-hoc* comparisons revealed that on channel 24, which is localized in the right inferior frontal gyrus of the ventrolateral prefrontal cortex, the higher fit individuals had larger changes in cerebral oxygenation (for HbO, [$F_{(1, 54)} = 7.2$, $p < 0.01$ and $F_{(1, 54)} = 8.4$, $p < 0.01$, in naming and executive condition respectively]; and HbT [$F_{(1, 54)} = 8.2$, $p < 0.01$ and $F_{(1, 54)} = 7.5$, $p < 0.01$, in naming and executive condition respectively]) than lower fit individuals on both conditions of the Computerized Stroop task. These results, depicted in the **Figure 5** suggest that higher fit had more activation in the right inferior frontal gyrus when performing the Stroop task. We found no

Table 1 | Means and standard deviations for the neuropsychological, mood and aerobic fitness assessment data in higher and lower fit participants.

	Younger	Older		Younger			Older		
	Total	Total	Age ES (d)	Higher fit	Lower fit	Fitness ES (d)	Higher fit	Lower fit	Fitness ES (d)
Age	24.6 ± 3.6	62.9 ± 5.4	–	24.5 ± 3.1	23.5 ± 5.3	–	63.0 ± 3.1	60.8 ± 5.6	–
Education (years)	17.09 ± 1.9	15.7 ± 3.7	–	17.69 ± 1.7	15.5 ± 1.38	–	15.69 ± 3.1	15.5 ± 5.1	–
BDI/GDS (/30)	1.9 ± 2.0	3.5 ± 4.4	0.4	2.5 ± 2.8	1.7 ± 1.7	0.3	1.7 ± 1.6	3.9 ± 4.8	0.6
MMSE (/30)	–	28.67 ± 1.0	–	–	–	–	28.17 ± 1.0	28.77 ± 1.2	0.5
SHORT TERM AND WORKING MEMORY									
Forward span	9.9 ± 2.5	10.0 ± 2.5	0.0	10.2 ± 2.9	9.17 ± 1.2	0.5	10.3 ± 2.4	8.5 ± 1.6	0.8
Backward span	6.9 ± 2.6	6.9 ± 2.1	0.0	7.3 ± 2.4	6.0 ± 2.9	0.5	7.1 ± 2.2	5.8 ± 1.2	0.7
ATTENTION AND PROCESSING SPEED									
Similarities	26.6 ± 4.8	23.9 ± 4.0$^{\#}$	0.6	26.9 ± 5.1	25.8 ± 4.5	0.2	24.5 ± 3.8	21.1 ± 4.5	0.8
Substitution	90.5 ± 12.1	69.7 ± 11.6$^{\#}$	1.7	83.8 ± 12.4	93.1 ± 9.9	0.8	69.2 ± 12.2	72 ± 8.4	0.2
PERCEPTUAL ABILITIES AND PROCESSING SPEED									
Trail A (s)	25.9 ± 8.8	35.0 ± 10.5$^{\#}$	0.9	25.5 ± 8.8	27.1 ± 9.7	0.2	35.3 ± 11.2	33.6 ± 6.0	0.2
Stroop—reading (s)	19.6 ± 2.7	20.2 ± 3.8	0.2	19.5 ± 2.6	19.7 ± 3.3	0.1	19.8 ± 4.0	22.6 ± 1.7	1.0
Stroop—color naming (s)	26.2 ± 4.5	29.2 ± 5.5	0.6	25.7 ± 3.9	27.7 ± 6.1	0.4	28.2 ± 5.3	34.0 ± 4.0	1.2
COGNITIVE INHIBITION AND FLEXIBILITY									
Trail B (s)	53.8 ± 17.8	77.2 ± 21.3$^{\#}$	1.2	51.9 ± 15.0	58.8 ± 24.8	0.3	75.6 ± 19.7	85.2 ± 28.7	0.4
Stroop—inhibition (s)	43.5 ± 9.2	56.1 ± 13.4$^{\#}$	1.1	41.9 ± 7.0	47.6 ± 13.5	0.5	54.4 ± 12.4	64.5 ± 16.0	0.7
Stroop—switching (s)	50.9 ± 13.6	56.5 ± 15.0	0.4	49.5 ± 15.1	54.7 ± 8.1	0.4	54.8 ± 15.1	64.4 ± 11.0	0.7
AEROBIC FITNESS									
MAQ	4.9 ± 2.1	4.0 ± 2.9	0.3	5.6 ± 1.7	4.2 ± 2.5	0.6	3.9 ± 2.4	4.2 ± 3.4	0.1
$\dot{V}O_{2max}$(ml.min^{-1}.kg^{-1})	43.8 ± 8.0	28.7 ± 7.3$^{\#}$	1.9	46.6 ± 7.0	36.4 ± 5.3*	1.6	30.1 ± 1.5	21.4 ± 7.1*	1.7

Results are presented mean ± SD.

$^{\#}$*Different from younger $p < 0.05$.*

**Different from high fit $p < 0.05$; ES (d), Cohen's d (Effect Size); MMSE, Mini Mental State Examination; BDI, Beck Depression Inventory; GDS, Geriatric Depression Scale; MAQ, Modifiable Activity Questionnaire; $\dot{V}O_{2max}$, Maximal Oxygen Uptake.*

effect of age and condition in the NIRS data. All NIRS results (concentration changes) are presented in **Table 3**.

DISCUSSION

The aim of this study was to assess the association between cardiorespiratory fitness level, cerebral oxygenation and cognitive performances in younger and older women. Based on the existing literature, we hypothesized that the cardiorespiratory fitness level would selectively enhance executive functioning in a computerized Stroop task. Secondly, we hypothesized that better executive control in higher fit people would be related to increased cerebral oxygenation. The results of this study supported our first hypothesis, as we found that regardless of age, individuals with a higher $\dot{V}O_{2max}$, perform better in the executive condition of the computerized Stroop task than individuals with a lower fitness level (lower $\dot{V}O_{2max}$). Additionally, this effect was specific to switching (executive) conditions and did not emerge in naming (non-executive) conditions. For our second hypothesis, we found a greater amplitude response in cerebral oxygenation evoked during the Stroop task, in women with higher fitness levels than in women with lower fitness levels. Our results highlight the right inferior frontal gyrus as being selectively more activated in higher fit women in comparison to lower fit women, an effect that was independent of age group.

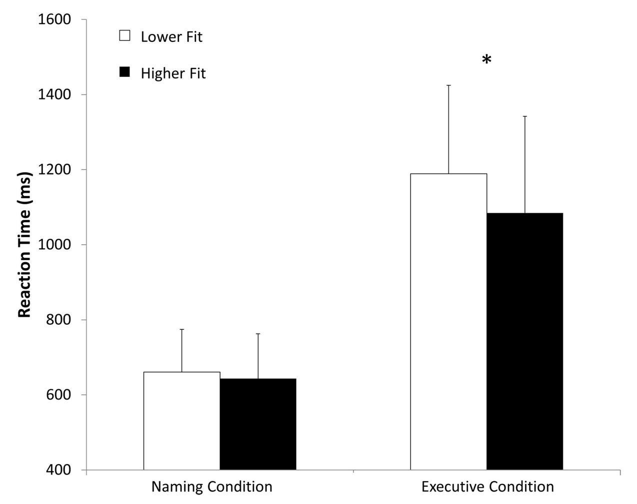

FIGURE 4 | Mean reaction time (ms) in naming and executive conditions for higher fit and lower fit women. *$p < 0.05$.

Regarding our cognitive performance results, the interaction age by condition in the trail test, the paper pencil version of Stroop and the computerized Stroop confirm that the age is accompanied by a decline in cognitive function and more specifically in the executive domain. Also our findings are in accordance with reviews (Hall et al., 2001; Bherer et al., 2013), a meta-analysis (Colcombe and Kramer, 2003) and recent longitudinal and cross sectional studies (Boucard et al., 2012; Predovan et al., 2012) that have demonstrated that older adults with higher fitness levels show specific physical training benefits in the executive function domain. Our findings are in line with, Boucard et al. (2012), who found in older people, a specific effect of cardiorespiratory fitness level only in inhibition (executive condition) and not in non-executive conditions. Similarly, our results align with, Predovan et al. (2012) who reported a specific aerobic training effect in the switching condition of the Stroop task after only 3 months of training in older adults. In addition, consistent with our results, these authors do not report a significant effect of aerobic training in the non-executive conditions of the Stroop task. All these results suggest that cardiorespiratory fitness has a specific positive impact on executive function. It is important to note that new evidence suggests that general improvements in fitness can also selectively improve executive functions. Indeed, Smiley-Oyen et al. (2008) found that aerobic training and resistance training selectively improve the executive functions of older adults. Our results support a positive association between cardiorespiratory fitness level and executive function performance and that the neurophysiological adaptations in the brain regions implicated in executive control are likely at the root of this selective improvement. Although, the anterior cingulate cortex is implicated in response conflict, prefrontal cortex structures contribute to a large range of high-level cognitive functions. Our findings support the proposal that higher cardiovascular fitness might improve functioning in prefrontal brain regions which are sensitive to age-related changes. Indeed, while the aging process is

Table 2 | Means and Standard deviations of reaction times and accuracy (%) during both conditions of the Computerized Stroop task.

	Younger	Older		Younger			Older		
	Total	Total	Age ES (d)	Lower fit	Higher fit	Fitness ES (d)	Lower fit	Higher fit	Fitness ES (d)
REACTION TIME (MS)									
Naming condition (ms)	567.1 ± 109.7	695.7 ± 94.4$^{\#}$	1.2	642.4 ± 146.9	538.9 ± 80.5	0.8	679.3 ± 78.3	699.0 ± 98.2	0.2
Executive condition (ms)	907.7 ± 224.8	1227.7 ± 185.7$^{\#}$	1.5	1091.5 ± 237.3	838.9 ± 182.7*	1.2	1286.5 ± 206.8	1215.9 ± 185.0*	0.4
ACCURACY (%)									
Naming condition (%)	99.4 ± 1.2	99.0 ± 1.9	0.2	99.5 ± 1.2	99.4 ± 1.2	0.1	99.5 ± 1.2	98.9 ± 2.0	0.3
Executive condition (%)	94.9 ± 4.5	89.2 ± 9.4	0.7	90.5 ± 2.9	96.5 ± 3.9	1.7	88.8 ± 3.9	89.3 ± 10.2	0.1

Results are presented mean ± SD.

$^{\#}$*Different from younger $p < 0.05$.*

**Different from high fit $p < 0.05$; ES (d), Cohen's d (Effect Size).*

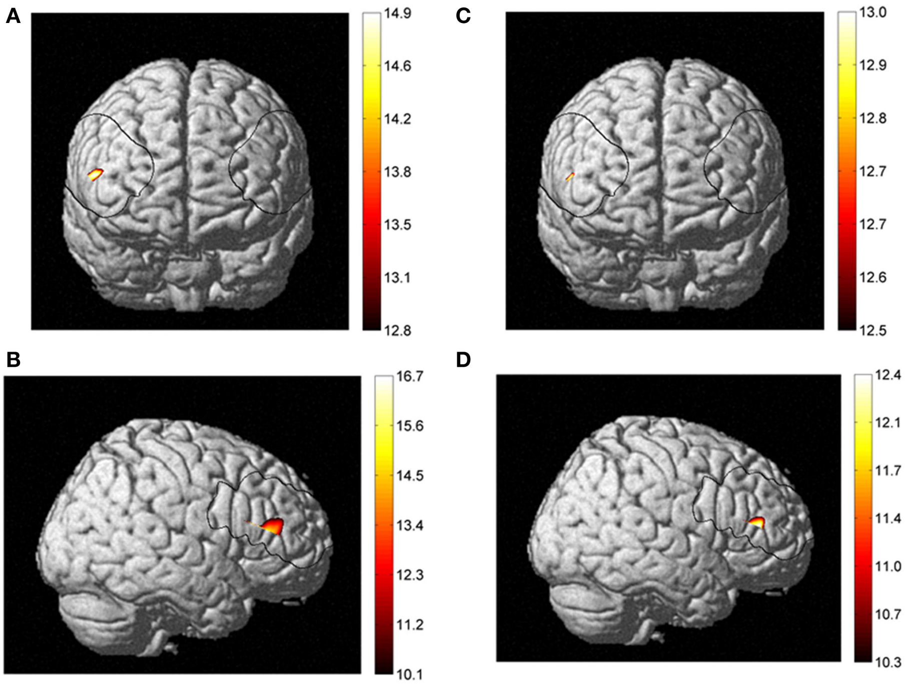

FIGURE 5 | Fitness effect between higher fit and lower fit women for HbO_2 in frontal (A) and right sagittal view (B), and for HbT in frontal (C) and right sagittal view (D).

Table 3 | Means and Standard deviations of cerebral changes (Δ) from baseline during both conditions of the Computerized Stroop task.

	Lower fit			Higher fit			Fitness ES (d)		
	ΔHbT (A.U)	**ΔHbO_2 (A.U)**	**ΔHbr (A.U)**	**ΔHbT (A.U)**	**ΔHbO_2 (A.U)**	**ΔHbr (A.U)**	**ΔHbT**	**ΔHbO_2**	**ΔHbr**
Naming condition	−0.93 ± 1.83	−1.29 ± 2.08	0.92 ±1.78	0.57 ± 1.63*	0.49 ± 1.81*	0.16 ± 1.32	0.9	0.9	0.5
Executive condition	−1.28 ± 1.86	−1.56 ± 2.25	0.93 ± 3.09	0.68 ± 2.10*	0.54 ± 2.33*	−0.15 ± 2.45	1.0	0.9	0.4

Results are presented mean ± SD; AU, arbitrary unit.

**Different from lower fit $p < 0.05$; ΔHbO_2, changes in oxyhemoglobin concentrations; ΔHbr, changes in deoxyhemoglobin concentrations; ΔHbT, changes in total hemoglobin. ES (d), Cohen's d (Effect Size).*

accompanied by brain atrophy that tends to be greatest in the frontal lobe, this decline can be moderated by fitness level (Yuki et al., 2012).

Of the research studies that have reported better cognitive functioning is associated with higher cardiorespiratory fitness levels; those that examined brain activity during cognitive performance have typically found that this is accompanied by an increased activation in the brain. For example, Colcombe et al. (2004) found a higher activation in different frontal and parietal regions during a Flanker task for higher fit older adults as compared to sedentary control people. Also, Rosano et al. (2010) reported that after 12 months of aerobic training, there was a higher activation in dorsolateral prefrontal cortex during the Digit symbol substitution test. In a cross-sectional study, Prakash et al. (2011) also found greater blood oxygen level dependent (BOLD) signal increases in the prefrontal and the parietal cortex during the executive Stroop conditions for older people who demonstrated a higher $\dot{V}O_{2max}$. Taken together, these results suggest that a higher cardiorespiratory fitness level is related to higher task-evoked hemodynamic responses in frontal, parietal and temporal areas and better cognitive functioning. Our results are in accordance with these findings since we found, regardless of age, greater response amplitude in the ΔHbO and ΔHbT NIRS signal for higher fit in comparison to lower fit individuals, during the Stroop task. In this study, we found negative value for ΔHbO and ΔHbT in both Stroop conditions for the lower fit subjects. Since, the NIRS signal is a change score, the negative value means a decrease of cerebral oxygenation during cognitive task from baseline (rest). So, the lower fit individuals may not have had enough oxygenated blood to meet the demand during task performance, they may generally have lower resting values, or their blood flow may not be as efficient as higher fit individuals. A decrease of cerebral oxygenation could be due to an important vasoconstriction of cerebral blood vessel. According to recent review (Huang et al., 2014), it's well known that the lower fit individuals presented higher stress (i.e., sympathetic activity) response during cognitive task compared to higher fit individuals. This physiological phenomenon could be involved in the decrease of cerebral oxygenation. However, within the current study, we do not have all the measures necessary to tease-out why the lower fit individuals have negative values and future research is needed to clarify this result. Furthermore, we need to keep in mind that the brain hemodynamic changes associated with fitness level are not systematically manifested by a higher functional activation signal but can in some instances also lead to a decrease in hemodynamic response in certain brain regions and during certain cognitive tasks (Brehmer et al., 2014). In some studies, the decreases in cerebral activity actually suggest a more efficient brain processing in those that are higher fit in comparison to those that are lower fit (Brehmer et al., 2014). However, our results seem to support that higher physical activity levels and greater cardiorespiratory fitness are associated with greater activity in prefrontal regions and better cognitive performance.

Several neurophysiological adaptations inherent to physical activity level, could explain these functional activation changes. Previous reports suggest that better cognitive performance in individuals with higher fitness level are associated with an increase in gray (Colcombe et al., 2003; Weinstein et al., 2012; Yuki et al., 2012) and white matter volume (Colcombe et al., 2003; Johnson et al., 2012; Tseng et al., 2013) and an increased hippocampal volume (Chaddock et al., 2010; Erickson et al., 2011). Weinstein et al. (2012) and Yuki et al. (2012) found that active people had a greater gray matter volume in pre-frontal lobe than less active people. In addition to the potential fitness benefits to the size and structures of the brain, fitness related changes in the vascular health of the brain could also explain our results. Indeed, Davenport et al. (2012), put forward the hypothesis that the cerebrovascular reserve could be the link between cardiorespiratory fitness level and cognition. Certainly, it is well known that higher fit people demonstrate a greater cerebrovascular health and better compliance in endothelial function (Bolduc et al., 2013). Using neuroimaging measures several researchers (Bailey et al., 2013; Murrell et al., 2013) have found that higher fit people demonstrate a higher cerebral blood flow at rest and during exercise. Recently, using MRI techniques, Xu et al. (2014) found that the cerebrovascular perfusion is improved by strength training. However, none of these studies evaluated the impact of improved vascular health on cognition. To support that greater cerebrovascular perfusion and oxygenation is associated with improved cognitive performance, Pereira et al. (2007) reported that after 3 months aerobic training with middle-aged adults, cerebral blood volume in the dentate gyrus of the hippocampus was increased and associated with improved $\dot{V}O_{2max}$, suggesting better vascularization. This better vascularization was in line with improvements in declarative memory performance. More recently, Brown et al. (2010), observe that physically women had a greater cerebrovascular responsiveness during exercise in hypercapnia than sedentary women and this responsiveness was correlated to better cognitive functioning. The greater cerebrovascular reserve and vascular compliance is probably mediated by an angiogenesis induced by liberation of neurotrophic factors such as BDNF, insulin-like growth factor (IGF) or vascular endothelial growth factor (VEGF). Also, it's well known that cardiorespiratory fitness improves vasoreactivity and improves endothelial function leading to better perfusion and better brain functioning (Bolduc et al., 2013; Voelcker-Rehage and Niemann, 2013). Our results are in accordance with all these previous findings and more specifically with recent research by Fabiani et al. (2014) that measured cerebral oxygenation with NIRS technique and found that higher fit older adults have a greater response in HbO_2 during visual task. The current findings support the hypothesis that neurovascular coupling is impaired in low-fit older adults. Our results are consistent with a decreased vascular reactivity in lower-fit older adults. A possible explanation for this is that the vascular system may have lost some of its capacity to adapt to stimuli demands. Also Fabiani et al. (2014), put forward the hypothesis that the lower fit older adults may suffer from decreased cerebral capillary density. This is consistent with the notion that aerobic exercise leads to an increase in angiogenesis, and thus increased perfusion, and that this can lead to improved executive function (Davenport et al., 2012; Fabiani et al., 2014).

Interestingly, our contrast analysis between higher and lower fit individuals revealed a posteriori that the right inferior frontal gyrus was more perfused during both conditions of our computerized Stoop task. This result is in accordance with previous reports using other neuroimaging techniques and highlights the possible implication of this region of interest in better cognitive functioning for higher fit individuals. Colcombe et al. (2004) found that frontal and prefrontal cortex structures showed greater hemodynamic signal increases during a Flanker task (i.e., inhibition task). These authors reported that the right middle frontal gyrus showed greater signal increases for physically active older people. The current finding supports a greater involvement of right prefrontal cortex structures in executive tasks in higher fit individuals. In line with these findings, Voelcker-Rehage et al. (2010) found that the functioning of the right inferior frontal gyrus was modified by physical fitness level during a Flanker task (i.e., inhibition task) and that it could be implicated to better cognitive functioning in highly physically active people. More recently Weinstein et al. (2012), found that the association between aerobic fitness and executive function may be partly mediated by prefrontal cortex volume. More specifically, volume of the right inferior frontal gyrus mediated the relationship between cardiorespiratory fitness and Stroop interference. We would propose that a greater volume in gray matter is associated to better perfusion and this may explain why we found a greater HbO and HbT signals during cognitive tasks in higher fit subjects. In cognitive domain, the right inferior frontal gyrus (rIFG) is one of region of interest (ROI) largely implicated in the executive function and inhibitory control (Aron et al., 2004, 2014; Forstmann et al., 2008). We found that this ROI was more activated in both non-executive and executive conditions. One of the possible explanations is that the rIFG is typically involved in inhibitory control and during conditions requiring attentional control. Hampshire et al. (2010) found that rIFG is recruited when important cues are detected, regardless of whether that detection is followed by the inhibition of a motor response, the generation of a motor response, or no external response at all. However, the role of the rIFG in improved executive functioning in higher fit individuals needs to be interpreted with caution and future research is necessary to confirm its role and sensitivity to physical training.

CONCLUSION

In conclusion, this study supports the positive association between a higher cardiorespiratory fitness level and cognitive performance in younger and older women. The results indicate that regardless age, the higher fit individuals performed better in executive conditions than lower fit individuals. These results support previous findings that demonstrate that the executive domain is most sensitive to physical fitness level and that this relationship is likely mediated by neurophysiological changes in prefrontal cortex. Indeed, we did find that higher fit individuals demonstrated an increased task-induced oxygenation response in the right inferior gyrus during both conditions of Stroop task in comparison to lower fit individuals. Improved performance and oxygenation response suggest that independent of age, higher fitness levels can lead to both physiological and behavioral benefits.

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BDNF mediates improvements in executive function following a 1-year exercise intervention

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Executive function declines with age, but engaging in aerobic exercise may attenuate decline. One mechanism by which aerobic exercise may preserve executive function is through the up-regulation of brain-derived neurotropic factor (BDNF), which also declines with age. The present study examined BDNF as a mediator of the effects of a 1-year walking intervention on executive function in 90 older adults (mean age = 66.82). Participants were randomized to a stretching and toning control group or a moderate intensity walking intervention group. BDNF serum levels and performance on a task-switching paradigm were collected at baseline and follow-up. We found that age moderated the effect of intervention group on changes in BDNF levels, with those in the highest age quartile showing the greatest increase in BDNF after 1-year of moderate intensity walking exercise ($p = 0.036$). The mediation analyses revealed that BDNF mediated the effect of the intervention on task-switch accuracy, but did so as a function of age, such that exercise-induced changes in BDNF mediated the effect of exercise on task-switch performance only for individuals over the age of 71. These results demonstrate that both age and BDNF serum levels are important factors to consider when investigating the mechanisms by which exercise interventions influence cognitive outcomes, particularly in elderly populations.

Keywords: BDNF, executive function, aging, exercise, physical activity, cognition, mediation analysis

INTRODUCTION

Decline in processing speed, memory, and executive function is a relatively widespread characteristic of aging (Li et al., 2001; Bishop et al., 2010; Silver et al., 2011; El Haj and Allain, 2012; Singh-Manoux et al., 2012; Woodard et al., 2012). Several neural mechanisms thought to support these cognitive processes become particularly vulnerable during the aging process (Burke and Barnes, 2006). For instance, brain-derived neurotrophic factor (BDNF) levels tend to decrease progressively with age (Lommatzsch et al., 2005; Ziegenhorn et al., 2007; Driscoll et al., 2012) and correlate with age-related reductions in hippocampal volume (Erickson et al., 2010a). BDNF facilitates neural repair (Yang et al., 2014), induces long-term potentiation (Diógenes et al., 2011), enhances learning and memory (Pang and Lu, 2004; Bekinschtein et al., 2014), and promotes synaptic plasticity and neurogenesis (Oliff et al., 1998; Lu, 2003; Vaynman et al., 2004). The beneficial effects of BDNF on brain health and cognition may be especially relevant for older adults, who are susceptible to physiological changes that interfere with neural processes and cognitive function. For instance, marked increases in blood pressure and inflammatory load occur in older adulthood, both of which have been independently linked to dementia risk and decline in cognitive function (Schmidt et al., 2002; Singh and Newman, 2011). Thus, there is an increased presence of factors that compromise cognitive function in older adults, with a contemporaneous decrease in known mechanisms that support advantageous brain and cognitive health. Therefore, efforts to increase BDNF, particularly in older aged individuals, could play an important role in the preservation of cognitive function.

Fortunately, exercise may be an effective approach to preserve and improve cognitive function and brain health in late adulthood. For example, randomized clinical trials have found that moderate-intensity exercise improves memory and executive function (Kramer et al., 1999a; Colcombe and Kramer, 2003; Smith et al., 2010) increases prefrontal cortex (Colcombe et al., 2006) and hippocampal volume (Erickson et al., 2011), and influences brain network connectivity (Voss et al., 2010a). Cross-sectional and epidemiological studies have supported these results and demonstrate that higher fitness levels and greater amounts of physical activity are associated with greater gray matter volumes (Erickson et al., 2010b; Weinstein et al., 2012; Benedict et al., 2013), white matter integrity (Gow et al., 2012; Gons et al., 2013; Tian et al., 2014), reduced brain atrophy rates (Gow et al., 2012; Smith et al., 2014), and reduced risk of cognitive impairment and dementia (Podewils et al., 2005; Larson et al., 2006; Sofi et al., 2011). Yet, the mechanisms by which exercise improves or maintains brain health in humans remain poorly understood, but likely include changes in inflammation, insulin resistance, as well as central changes in serotonin, dopamine, or other neurotransmitters.

Increased expression of BDNF may be another mechanism by which exercise positively influences cognitive and brain function. For example, in rodents, exercise increases BDNF expression in the striatum (Marais et al., 2009), hippocampus (Aguiar et al., 2011), and cortex (Neeper et al., 1996) and an exercise-induced up-regulation of BDNF, along with its receptor tyrosine kinase (Li et al., 2008), mediates the effects of exercise on cognition (Gómez-Pinilla et al., 2002; Vaynman et al., 2004; Van Praag et al., 2005; Stranahan et al., 2009; Creer et al., 2010; Bechara and Kelly, 2013). Unfortunately in humans the effect of exercise on serum BDNF is more equivocal (Zoladz and Pilc, 2010). Acute bouts of exercise increase serum BDNF levels, which, in turn, are associated with improvements in cognitive performance (Knaepen et al., 2010; Ströhle et al., 2010; Heyman et al., 2012; Coelho et al., 2013). However, more chronic and longer-term exercise programs have not reliably demonstrated increases in BDNF levels (Baker et al., 2010; Erickson et al., 2011; Ruscheweyh et al., 2011). Despite these discouraging effects of exercise interventions, exercise-induced changes in hippocampal volume (Erickson et al., 2011) and brain connectivity (Voss et al., 2013) were correlated with percent change in serum BDNF levels. These findings suggest that serum BDNF levels may be an important biomarker for brain and cognitive health, but whether BDNF mediates the positive effects of exercise on cognitive performance remains a matter of speculation.

Here, we examine whether exercise-induced changes in serum BDNF mediates the effect of a randomized exercise intervention on executive function. Specifically, we assessed effects on task-switch performance, a cognitive task largely susceptible to age-related shifts in performance speed and accuracy (Salthouse et al., 1998; Kray and Lindenberger, 2000; Cepeda et al., 2001; Jimura and Braver, 2010; Gazes et al., 2012). This task is considered a measure of executive control and is supported primarily by the prefrontal and parietal cortices (Sohn et al., 2000; Braver et al., 2003; Aron et al., 2004; Gold et al., 2010), regions that experience preferential degeneration with advancing age (Sowell et al., 2003; Salat et al., 2005; Driscoll et al., 2009). Because BDNF levels decline with age (Lommatzsch et al., 2005; Burke and Barnes, 2006; Ziegenhorn et al., 2007), and is found in cortical regions that likely support task-switch performance (Podewils et al., 2005; Aguiar et al., 2011; Diógenes et al., 2011), we reasoned that age might be an important moderator of the effects of exercise on BDNF and task-switch performance.

Prior studies examining the effects of exercise on serum BDNF have used age as a covariate rather than modeling age as an interaction term. Yet, several studies and meta-analyses suggest that the positive effects of exercise on cognitive performance may be magnified at older ages (Etnier et al., 2007; Smith et al., 2010) while others have found that age-related losses in gray matter volume and n-acetylaspartate levels were mitigated by higher fitness levels (Colcombe et al., 2003; Erickson et al., 2012). These and other studies (Adlard et al., 2005; Knaepen et al., 2010) suggest that age might be moderating an effect of exercise on serum BDNF levels.

The current study examined the effects of a 12-month randomized exercise intervention on serum BDNF and task-switching performance in older adults. We predicted that exercise-induced changes in serum BDNF would mediate the effects of the exercise intervention on task-switch performance. However, we also predicted that age would moderate the effect of the intervention on BDNF levels, such that the oldest adults in the exercise group would show greater increases in BDNF than their younger counterparts.

METHOD

PARTICIPANTS

One-hundred and seventy-nine participants were randomly assigned to either a walking exercise or stretching-toning control group prior to the start of the intervention. Of the 179 participants, 106 had complete blood data collected at baseline and post-intervention for BDNF assays. Additionally, 13 participants were missing *BDNF* genetic polymorphism data and were excluded from the analysis. We also excluded one participant who was ill at the time of blood draw. Our final sample in BDNF analyses consisted of 92 participants. There were an additional two individuals missing task-switching data (one from each group), so all analyses conducted with the task-switch data used a sample of 90 participants. Excluded participants did not differ in demographic characteristics or baseline fitness level from those included ($p > 0.05$). The sample and results from this intervention have been previously reported, where hippocampal volume (Erickson et al., 2011), brain connectivity (Voss et al., 2010a,b, 2013) white matter integrity and adherence to the intervention (McAuley et al., 2011) were examined. The analyses and results reported in the current study have not been previously examined, nor published.

Community-dwelling older adults were recruited from the local community of Urbana-Champaign, Illinois. Eligible participants had to (*i*) demonstrate strong right handedness (Oldfield, 1971), (*ii*) be between the ages of 55 and 80, (*iii*) score ≥51 on the modified Mini-Mental Status Examination (Stern et al., 1987), (Singh-Manoux et al., 2012), score <3 on the Geriatric Depression Scale to rule out possible depression (Yesavage and Sheikh, 1986), (*v*) have normal color vision, (*vi*) have a corrected visual acuity of at least 20/40, (*vii*) have no history of neurological diseases or infarcts, including Parkinson's disease, Alzheimer's disease, multiple sclerosis, or stroke, (*viii*) have no history of major vasculature problems, including cardiovascular disease or diabetes, (*ix*) obtain consent from their personal physician, and (*x*) sign an informed consent form approved by the University of Illinois. In addition, all participants had to report being currently sedentary, which was defined as having been physically active for 30 min or more no more than two times in the last 6 months. Participants were compensated for their participation. The Institutional Review Board of the University of Illinois approved the study and all participants gave written informed consent prior to participating.

After completion of the initial blood draw, an MRI session (results not included here), and fitness assessment, participants were randomized to the aerobic walking group ($n = 47$) or to the stretching-toning control group ($n = 45$). Demographic information can be found in **Table 1**.

AEROBIC FITNESS ASSESSMENT

Maximal oxygen uptake (VO_{2max}) was used as an objective measure of baseline cardiorespiratory fitness. Participants were required to obtain consent from their personal physician before cardiorespiratory fitness testing was conducted. As detailed by Voss et al. (2010a) assessment of cardiorespiratory fitness was determined using graded maximum exercise testing on a motor-driven treadmill with continuous monitoring of respiration, heart rate, and blood pressure by a cardiologist and nurse (Voss et al., 2010a, 2013). During the assessment, subjects walked at a speed slightly faster than their normal walking pace with increasing graded increments of 2% every 2 min. Oxygen uptake was measured at 30-s intervals until a max VO_2 was attained or to the point of test termination due to exhaustion. VO_{2max} was defined as the highest recorded VO_2 value when two of three criteria were satisfied: (1) a plateau in VO_2 peak between two or more workloads, (2) a respiratory exchange ratio >1.00, or (3) a heart rate equivalent to their age predicted maximum (i.e., 220-age). VO_{2max} scores are expressed in units of milliliters per kilogram per minute (ml/kg/min), after controlling for height and weight of the individual.

Table 1 | Demographics, fitness, and BDNF.

Variable	Total sample $N = 92$	Walking group $N = 47$	Control group $N = 45$
% Men	35.9%	31.90%	40.00%
Age (years)	66.82 (5.59)	67.23 (5.39)	66.38 (5.83)
EDUCATION %			
High School	19.6%	19.1%	20%
Part College/Vocational	30.4%	36.2%	24.4%
Bachelor's Degree	16.3%	12.8%	20%
Master's Degree	21.7%	23.4%	20%
PhD or Equivalent	12%	8.5%	15.6%
VO_{2max}(mL/kg)	21.51 (4.68)	21.22 (4.62)	21.82 (4.78)
Pre-intervention BDNF (pg/mL)	21,909.96 (9147.95)	21,736.91 (9768.31)	22,090.69 (8558.71)
Post-intervention BDNF (pg/mL)	22,897.03 (8293.85)	24,067.78 (7814.90)	21,674.24 (8684.70)
BDNF met allele carriers	7	2	5

Demographic information comparing the two intervention groups: walking intervention, stretching and toning control.

TRAINING PROTOCOL

Aerobic exercise condition

For the aerobic exercise program, a trained exercise leader supervised all sessions. As described by McAuley et al. (2011) and Erickson et al. (2011), participants started by walking for 10 min and increased walking duration weekly by 5-min increments until a duration of 40 min was achieved at week 7. Participants walked for 40 min per session for the remainder of the program. All walking sessions started and ended with approximately 5 min of stretching for the purpose of warming up and cooling down. Participants wore heart rate monitors and were encouraged to walk in their target heart rate zone, which was calculated using the Karvonen method (Strath et al., 2000) according to the resting and maximum heart rates achieved during the baseline maximal graded exercise test. The target heart rate zone was 50–60% of the maximum heart rate reserve for weeks 1–7 and 60–75% for the remainder of the program. Participants in the walking group completed an exercise log at each exercise session. Every 4 weeks, participants received written feedback forms that summarized the data from their logs. Participants with low attendance and/or a low exercise heart rate were encouraged to improve their performance in the following month.

Stretching and toning control condition

For the stretching and toning control program, all sessions were led and monitored by trained exercise leaders. All classes started and ended with warm-up and cool-down stretching. During each class, participants engaged in four muscle-toning exercises using dumbbells or resistance bands, two exercises designed to improve balance, one yoga sequence, and one exercise of their choice. To maintain interest, a new group of exercises was introduced every 3 week. During the first weeks, participants focused on becoming familiar with the new exercises, and during the second and third weeks they were encouraged to increase the intensity by using more weight or adding more repetitions. Participants in the stretching and toning control group also completed exercise logs at each exercise session and received monthly feedback forms. They were encouraged to exercise at an approximate intensity of 13–15 on the Borg Rating of Perceived Exertion scale (Borg, 1985) and to attend as many classes as possible.

SERUM BDNF ASSAY

Blood was collected at baseline before the intervention and again immediately after the completion of the program. Blood sampling for BDNF analysis was performed approximately 1 week before the cognitive testing session. Fasted subjects reported to the laboratory at 0600–0800 h, at which time blood from the antecubital vein was collected in serum separator tubes (Becton Dickinson). The blood samples were kept at room temperature for 15 min to allow for clotting, after which the samples were centrifuged at 1100 × g at 4°C for 15 min. Serum was then harvested, aliquoted, and stored at −80°C until analysis. Serum BDNF was quantified using an enzyme-linked immunosorbant assay (Human BDNF Quantikine Immunoassay, DBD00, R&D Systems) according to the manufacturer's instructions.

BDNF GENOTYPING

We used the BuccalAmp™ DNA Extraction Kit from Epicentre Biotechnologies (Madison, WI USA). Buccal cells were collected from Puritan sterile cheek swabs after rinsing the mouth with tap water. The rs6265 SNP was assayed by a combination of nested PCR and melting-curve analysis with T_m-shift primers (Wang et al., 2005). The DNA fragment was preamplified from genomic DNA (300 bp) and used as a template for second round (allele-specific) PCR on a Bio-Rad MyiQ thermal cycler, which allows automated melting temperature analysis of the PCR products. One allele-specific primer was designed with a 5′ GC tail, resulting in an easily detectable increase in the melting temperature of the PCR product. For rs6265, the forward and reverse primers used in the first PCR were 5′ ACTCTGGAGAGCGTGAATGG 3′ and 5′ CCAAAGGCACTTGACTACTGA 3′. In the second round PCR, the primer specific to the "G" allele (val) was 5′ GCGGGCAGGGCGGCTCATCCAA CAACTCTTCTAACAC 3′, the primer specific to the "A" allele (met) was 5′ TCATCCAACAACTCTTCTACCAT 3′ and the common primer was 5′ CCAAGGCAGGTTCAAG 3′. Genetic data was analyzed using a dominance model such that Met carriers were combined into a single group.

COGNITIVE ASSESSMENT

The task-switching paradigm is frequently used to assess executive processes (Kramer et al., 1999a; Kray and Lindenberger, 2000; Gratton et al., 2009; Gold et al., 2010; Jimura and Braver, 2010), including cognitive flexibility and inhibition (Verstynen et al., 2012). The task-switch paradigm was administered as part of a larger battery of tasks, but was selected for the present study because (1) it assesses executive functioning and (2) our previous studies have shown that this task is sensitive to exercise interventions (Kramer et al., 1999a,b). Therefore, we selected this task because it met criteria for testing mediation.

As described in Voss et al. (2010a), participants utilized color-based cues to determine whether they were to judge whether a number was odd or even, or whether it was low or high (i.e., smaller or larger than 5). The numbers were presented individually for 1500 ms against a pink or blue background. If the background was blue, participants had to determine whether the number was high ("X" key) or low ("Z" key). If the background was pink, participants were to report whether the number was odd ("N" key) or even ("M" key). In both cases, participants were asked to answer as quickly as possible (Voss et al., 2010a). Participants completed a practice block followed by two blocks of individually presented tasks, one block consisted of only the "high or low" task, and the other consisted of only the "odd or even" task. This was followed by a switching block, which included 120 trials with the task in each trial chosen randomly. In this block, some trials were repeated, referred to here as "repeat trials," and some trials switched between the two conditions, referred to here as "switch trials" (see **Figure 1** for task depiction).

Accuracy (% correct) and reaction time (RT) served as indices of performance on the task-switch test. Accuracy (% correct) and time (RT) was recorded separately for single trials, repeat trials within the mixed block, and switch trials within the mixed block. Local switch cost, the difference between repeat trials (when the preceding trial involved the same task) and switch trials (when the preceding trial involved a different task) was calculated for both RT and accuracy (Verstynen et al., 2012). Additionally, global switch cost, the difference between switch trials and single task trials, was calculated for RT and accuracy.

STATISTICAL ANALYSIS

All variables were tested for normality and skew. To assess whether age was inversely associated with serum BDNF, we conducted a multivariable linear regression analysis. *BDNF* genotype was included as a covariate in the model to adjust for effects of the val66met polymorphism on BDNF serum concentrations.

To examine whether the effect of exercise group (walking; stretching) on serum BDNF varied as a function of age, multivariable linear regression was employed using the bootstrap method with 10,000 resampling iterations. Therefore, main effects and interaction effects were estimated from the resampled data repeatedly drawn from the original dataset with replacement. Within the regression model, pre-intervention serum BDNF was included as a covariate to account for any group-level differences in serum BDNF at baseline. Gender and the *BDNF* val66met polymorphism were also adjusted for in the model. Exercise group and age were entered as predictor terms to determine whether age and group independently predicted change in serum BDNF. We also included an age × group interaction in order to test whether age moderated the effect of exercise group on change in serum BDNF.

We also predicted that age would moderate the association between exercise group and cognitive performance post-intervention. To test this hypothesis, we used multivariable linear regression adjusting for gender, years of education, baseline serum BDNF, the *BDNF* val66met polymorphism, and baseline cognitive performance. Thus, rather than modeling within-subject changes in cognitive performance, we assessed group-level differences in performance post-intervention, accounting for individual differences in performance at baseline. Again, bootstrapping was applied to the regression model, using 10,000 iterations. Also entered was group, age as a continuous variable, and their interaction product. A statistical threshold of $p < 0.05$ was used to determine significance for the linear regression analyses. Significant interactions revealed by the linear regression analyses were then subjected to repeated measures analysis of variance tests to assess within-subject changes from pre to post-intervention.

Finally, conditional process modeling was used to examine the conditional nature by which exercise group predicts cognitive function following the 1-year intervention. Using this procedure,

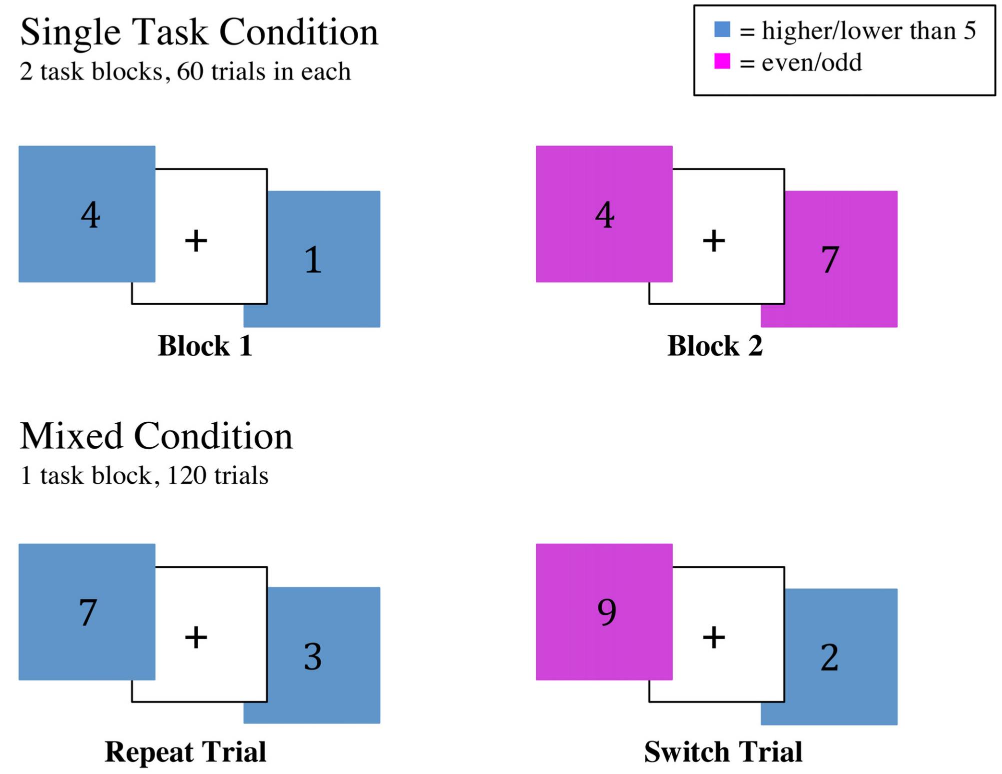

FIGURE 1 | Display of the task-switch paradigm. Participants were instructed to respond to a number between 1 and 9 (except for 5) that appeared centrally located on the computer screen. The background color (blue/pink) cued them as to the task they would do (Pink: even/odd; Blue: higher/lower than 5). In the single task condition participants were presented with blocks of a single task whereas in the mixed condition the two conditions were randomly presented.

we examined whether BDNF serum levels mediated the relationship between exercise group and cognitive performance, and whether the indirect effect of exercise group on cognitive performance through serum BDNF varied as a function of age. This technique estimates the mediating effect of serum BDNF on the relationship between exercise group and task-switch performance, while accounting for moderating effects of age on (1) the effect of exercise group on serum BDNF and (2) the direct effect of exercise group on task-switch performance. The model format and analyses were conducted using the PROCESS macro by Hayes (2013) in SPSS. This method provided an estimation of both the direct and indirect pathways, resulting in the calculation of 95% confidence intervals (CI) for both direct and indirect effects (see **Figure 2** for model depiction). The regression coefficients are displayed in unstandardized form, as the bootstrapped CI's correspond to the unstandardized effects rather than the standardized effects. Mediation results are considered significant if the CI's do not contain 0.

RESULTS

SUBJECT CHARACTERISTICS AT BASELINE

The exercise groups did not significantly differ in age, gender, years of education, serum BDNF, or VO_{2max} at baseline (all $p > 0.05$) (see **Table 1**). Additionally, there were no significant differences between groups on task switch performance indices at baseline (all $p > 0.05$; see **Table 2** for task switch accuracy and reaction time data pre and post-intervention).

AGE MODERATES THE EFFECT OF EXERCISE ON CHANGE IN SERUM BDNF

The *BDNF* val66met polymorphism was not related to serum BDNF at baseline ($r = 0.018$; $p = 0.868$). Nonetheless, in the regression analyses described below we continued to control for *BDNF* val66met variation because several prior studies have indicated a small, but significant, relation between serum BDNF and the *BDNF* val66met polymorphism (Lang et al., 2009). We also found that females had significantly higher levels of serum BDNF at baseline in this sample ($r = 0.266$; $p = 0.010$) and therefore included gender as a covariate in the analyses below. Consistent with our hypothesis, older ages were associated with lower serum BDNF levels prior to the start of the intervention ($t = -3.501$; $p = 0.001$), after controlling for gender and the *BDNF* val66met polymorphism.

Collapsed across the intervention and control groups, age did not predict change in serum BDNF over the 1-year period ($B = -77.69$; $p = 0.489$). Similarly, holding age constant, there was not a main effect of exercise group on change in serum BDNF following the intervention, although the association was trending ($B = 2652.27$; $p = 0.084$). However, the lack of main effects was qualified by a significant interaction between age and exercise

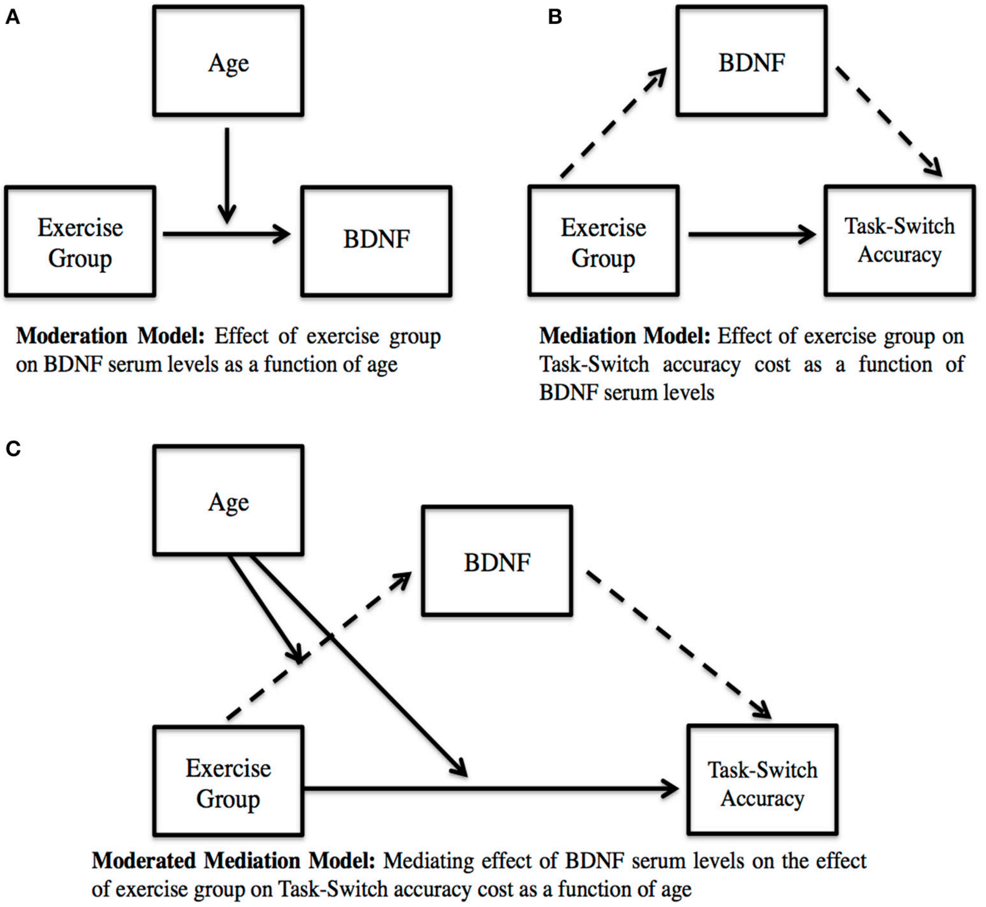

FIGURE 2 | Moderated mediation model. (A) Moderation Model: Effect of exercise group on BDNF serum levels as a function of age. **(B)** Mediation Model: Effect of exercise group on Task-Switch accuracy cost as a function of BDNF serum levels. Note: Solid arrow indicates direct pathway; Dashed arrow indicates indirect pathway. **(C)** Moderated Mediation Model: Mediating effect of BDNF serum levels on the effect of exercise group on Task-Switch accuracy cost as a function on age. Note: Solid arrow indicates moderation; Dashed arrow indicates mediation.

group on change in serum BDNF ($B = 471.95$; $p = 0.036$) (see **Table 3**). Specifically, across the 1-year intervention, the stretching and toning group showed a decline in BDNF levels for the oldest individuals. In contrast, there was a positive linear relationship between age and serum BDNF in the walking group, indicating that older aged individuals experienced the greatest increase in BDNF following 1-year of moderate intensity walking exercise (see **Figure 3B**).

For further exploration of this interaction, we used repeated measures analysis of variance and divided the sample into higher and lower aged individuals using the median value for age (Md age = 65). Serum BDNF at baseline and serum BDNF post-intervention were entered as the within subjects factor, age and exercise group were entered as between subjects factors, and *BDNF* genotype and gender were entered as covariates. Consistent with the results from the regression, participation in the walking group offset an age-related reduction in BDNF levels ($F = 5.45$; $p = 0.022$; $\eta_p^2 = 0.060$) (see **Figure 3**). In particular, 12 months of moderate intensity walking exercise increased serum BDNF levels among adults older than 65 years of age, while similarly aged individuals in the non-aerobic condition showed a decrease in serum BDNF over the 12-month intervention period.

AGE MODERATES THE EFFECT OF EXERCISE ON TASK-SWITCH PERFORMANCE

There was not a significant relation between education, baseline serum BDNF, or the *BDNF* val66met polymorphism and performance for any of the task switch outcomes (all $p > 0.05$). However, males had a smaller global accuracy cost at baseline ($r = -0.210$; $p = 0.046$), so gender was used as a covariate in the regression model below. Further, although education and BDNF serum and genotype were not significantly related to task-switch outcomes, we included these variables as covariates in the regression model since prior research has reported effects of education and BDNF on cognitive outcomes in late adulthood (Albert et al., 1995; Erickson et al., 2008; Gunstad et al., 2008). Including these variables in the model provides a more conservative estimate of the associations between exercise group, change in serum BDNF, and change in task-switch performance.

Table 2 | Task-switch performance.

Variable	Total sample $N = 90$	Walking group $N = 46$	Control group $N = 44$
Pre-intervention single accuracy	92.71%	93.13%	92.27%
Post-intervention single accuracy	96.48%	96.47%	96.50%
Pre-intervention repeat accuracy	82.49%	83.33%	81.64%
Post-intervention repeat accuracy	90.17%	92.36%	87.87%
Pre-intervention switch accuracy	77.02%	78.11%	75.91%
Post-intervention switch accuracy	88.86%	91.13%	86.49%
Pre-intervention local accuracy cost	−6.60%	−6.11%	−7.10%
Post-intervention local accuracy cost	−1.60%	−1.48%	−1.73%
Pre-intervention global accuracy cost	−15.69%	−15.02%	−16.36%
Post-intervention global accuracy cost	−7.96%	−5.45%	−10.58%
Pre-intervention single RT (ms)	774.64 (105.35)	774.62 (96.47)	774.67 (114.82)
Post-intervention single RT (ms)	758.97 (106.48)	757.29 (99.94)	760.75 (113.34)
Pre-intervention repeat RT (ms)	994.96 (197.07)	1000.27 (204.64)	989.69 (191.36)
Post-intervention repeat RT (ms)	986.17 (144.69)	991.13 (136.40)	980.88 (154.47)
Pre-intervention switch RT (ms)	1356.34 (194.80)	1358.90 (175.54)	1353.79 (214.32)
Post-intervention switch RT (ms)	1290.29 (239.18)	1298.98 (204.85)	1281 (273.27)
Pre-intervention local RT cost (ms)	361.37 (218.37)	358.63 (225.64)	364.10 (213.37)
Post-intervention local RT cost (ms)	304.12 (184.92)	307.86 (143.17)	300.12 (221)
Pre-intervention global RT cost (ms)	400.86 (163.48)	404.65 (148.15)	397.06 (179.12)
Post-intervention global RT cost (ms)	397.70 (153.57)	407.18 (140.35)	387.58 (167.59)

Demographic information comparing the two intervention groups: walking intervention, stretching, and toning control.

RT, Reaction Time; ms, milliseconds.

Table 3 | Age moderates effect of exercise group on BDNF serum levels at post-intervention.

	B	*SE*	*p*	LLCI	ULCI
COVARIATES					
Baseline serum BDNF	0.473**	0.109	0.0001	0.256	0.684
BDNF genotype	1152.29	2055.91	0.560	−2730.59	5415.26
Gender	1137.57	1834.59	0.535	−2555.65	4599.24
MAIN EFFECTS					
Age	−77.69	112.27	0.490	−303.22	142.03
Exercise group	2652.27	1472.59	0.078	−373.40	5429.23
INTERACTION					
Exercise group × Age	471.95*	1.735	0.039	26.261	919.647

Age as moderator of the effect of exercise group on serum BDNF post-intervention. Coefficients are unstandardized B-values calculated from bootstrap permutation of 10,000 iterations.

LLCI, lower-level confidence interval; ULCI, upper-level confidence interval.

$^*p < 0.05$; $^{**}p < 0.01$.

The linear regression model showed that there was not a main effect of group on global accuracy percent cost [(switch trial accuracy-single trial accuracy)/single trial accuracy] post-intervention ($B = 5.952$; $p = 0.097$), although the relation was trending. These results suggest that the control group demonstrated a marginally greater deficit in accuracy between single and switch trials relative to those in the walking group at post-intervention. Additionally, there was not a significant main effect of age on global accuracy cost ($B = -0.055$; $p = 0.868$). But, there was an interaction between age and exercise group on changes in global accuracy cost ($B = 1.645$; $p = 0.026$) (see **Table 4**). Decomposing this interaction revealed that global accuracy cost remained constant over the 12 month period across all ages within the aerobic exercise group. In contrast, within the stretching and toning control group, there was an age-related increase in percent accuracy cost following the 1-year intervention. Thus, while the magnitude of the global accuracy cost remained constant across all ages in the walking group, older aged individuals within the non-aerobic condition demonstrated a larger cost on performance following the 12-month intervention.

We probed the interaction using a repeated measures analysis of variance, and divided the sample into higher and lower aged individuals using the median age value (Md age = 65). Global accuracy cost at baseline and post-intervention were entered as the within subjects factor, age and exercise group were entered as between subjects factors, and gender, years of education, *BDNF* genotype, and serum BDNF at baseline were included as covariates. In accordance with the results from the regression analysis, age-related reduction in task performance was negated by participation in the aerobic exercise condition ($F = 5.19$; $p = 0.025$; $\eta_p^2 = 0.064$).

In contrast, there was not a significant main effect of exercise group ($B = 0.602$; $p = 0.633$) on local accuracy (switch accuracy − repeat accuracy/repeat accuracy) cost. There was also a non-significant relation between age and local accuracy cost ($B = 0.156$; $p = 0.103$) and a non-significant age × exercise group interaction on local accuracy cost ($B = 0.265$; $p = 0.136$).

Because of the significant effects on global accuracy cost, we conducted *post-hoc* analyses to examine percent accuracy separately for single trials, repeat trials, and switch trials, adjusting for gender, education, trial accuracy at baseline, baseline serum BDNF and the *BDNF* genotype. For single trial accuracy, there was not a main effect of age ($B = -0.051$; $p = 0.394$) or group ($B = 0.530$; $p = 0.361$) nor was there a significant age × group interaction ($B = -0.092$; $p = 0.433$). Similarly, there was not a direct effect of age ($B = -0.283$; $p = 0.438$) or group ($B = 3.384$;

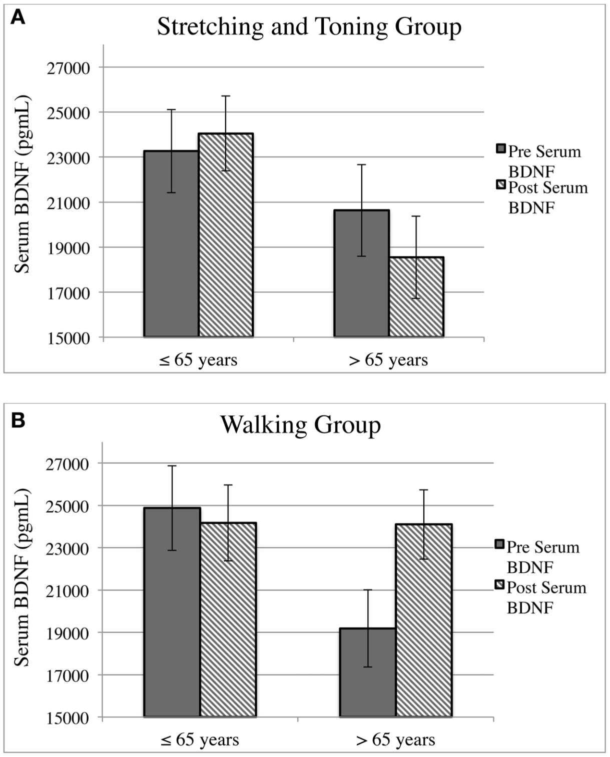

FIGURE 3 | Moderating effect of age (stratified). Note: Effects of exercise on serum BDNF as a function of age. Age stratified using a median split. **(A)** Serum BDNF decreases following the intervention in the control group among adults >65 years. **(B)** Serum BDNF increases following 1 year of walking exercise, specifically for adults aged >65 years.

$p = 0.352$) on repeat trial accuracy, or an age × group interaction term on repeat trial accuracy ($B = 0.747$; $p = 0.321$). Finally, there was not an effect of age ($B = -0.075$; $p = 0.832$), group ($B = 4.995$; $p = 0.154$), or their product ($B = 1.126$; $p = 0.124$) on switch trial accuracy. These results suggest that the significant age × group interaction on global accuracy cost was specific to global cost, a purer measure of cognitive flexibility, rather than performance on any specific trial type.

Age did not moderate the effect of exercise on RT for any of the variables, including single RT, repeat RT, switch RT, or switch cost (all $p > 0.05$).

BDNF MEDIATES EFFECT OF EXERCISE ON TASK-SWITCH PERFORMANCE AS A FUNCTION OF AGE

The prior analyses demonstrated that the effect of exercise group on BDNF serum levels and task-switch performance varied as a function of age. Specifically, relative to the non-aerobic control condition, 12 months of moderate intensity aerobic exercise led to an increase in serum BDNF and an improvement in task performance (lower cost on global accuracy) that varied with age, with the oldest individuals showing the greatest benefits. Next, we tested whether serum BDNF mediates the association between exercise group and change in global accuracy cost following the 1-year intervention. Additionally, due to the robust age effects observed, a moderated mediation conditional processes model was used to examine whether serum BDNF explained the relation between exercise group and task-switch performance as a function of age. Thus, we first examined whether serum BDNF mediated the relation between exercise group and global accuracy cost. Then, we assessed whether the mediating effect of serum BDNF varied as a function of age. For these analyses, we focused only on the task variables that showed a significant age × group interaction effect (i.e., global accuracy cost). Since gender, education, and the *BDNF* val66met polymorphism did not significantly modify any of the above outcomes, they were removed from subsequent mediation models.

Table 4 | Age moderates effect of exercise group on global task switch accuracy cost.

	B	*SE*	*p*	LLCI	ULCI
COVARIATES					
Baseline global accuracy cost	0.186*	0.085	0.035	0.039	0.375
Baseline serum BDNF	0.0001	0.0002	0.193	0.000	0.001
BDNF genotype	5.702	5.98	0.339	−4.002	18.473
Gender	3.816	3.515	0.289	−2.659	11.183
Education	2.279	1.297	0.093	−0.249	4.860
MAIN EFFECTS					
Age	−0.055	0.328	0.869	−0.717	0.576
Exercise group	5.952	3.420	0.099	−0.694	12.776
INTERACTION					
Exercise group × Age	1.645*	0.664	0.025	0.382	2.977

Age as moderator of the effect of exercise group on global accuracy cost post-intervention. Coefficients are unstandardized B-values calculated from bootstrap permutation of 10,000 iterations.

LLCI, lower-level confidence interval; ULCI, upper-level confidence interval.

$^*p < 0.05$.

Mediation analyses revealed that there was not a direct effect of exercise group on global accuracy cost, after accounting for baseline serum BDNF and baseline global accuracy cost [$B = 4.541$; $p = 0.160$; CI(SE) −1.831; 10.912 (3.203)]. In contrast, there was a significant indirect effect of exercise group on global accuracy cost through serum BDNF [$B = 1.317$; CI(SE).058; 4.66 (1.007)]. Specifically, participants in the walking group scored, on average, 1.36 percent better on global accuracy cost, which was mediated by exercise-induced changes in serum BDNF levels. The average global accuracy cost was negative (−7.96%) indicating a smaller performance deficit between single and switch trials. Thus, 1 year of moderate-intensity aerobic exercise increased levels of serum BDNF, which, in turn, led to a decrease in cost performance.

Further, the conditional process analysis showed that there was a conditional indirect effect of exercise group on global accuracy cost through BDNF serum that differed by age [$B = 0.168$; CI(SE).009; 0.567 (0.129)] (see **Table 5**). Further inspection revealed that serum BDNF levels mediated the relationship between exercise group and task-switch performance specifically for older aged individuals (see **Figure 4**).

While the above analyses included age as a continuous predictor, to determine the age at which effects of BDNF mediated task switch accuracy cost, age was divided into quintiles (10th, 25th, 50th, 75th, and 90th percentiles). Effects were then calculated for

Table 5 | Moderated mediation model of effects of exercise group on global accuracy cost.

	B	*SE*	*p*	LLCI	ULCI
COVARIATES					
Pre-intervention BDNF	0.0001	0.0002	0.584	−0.0003	0.0005
Baseline global accuracy cost	0.148*	0.062	0.020	0.024	0.271
MODERATED MEDIATION INDIRECT EFFECT					
Post-intervention BDNF	0.168*	0.129		0.008	0.568
Effect at 10% Age (60 years)	−0.130	0.957		−2.108	1.868
Effect at 25% Age (63 years)	0.373	0.807		−0.761	2.662
Effect at 50% Age (65 years)	0.79	0.799		−0.263	3.162
Effect at 75% Age (71 years)	1.714*	1.183		0.260	5.382
Effect at 90% Age (76 years)	2.553*	1.716		0.390	7.807

Moderated mediation model displaying BDNF as mediator of the effect of exercise group on post-intervention global accuracy cost (% correct) as a function of age. Includes overall effect and indirect effect of serum BDNF at different ages (stratified into quintiles).

**$p < 0.05$—based on confidence interval.*

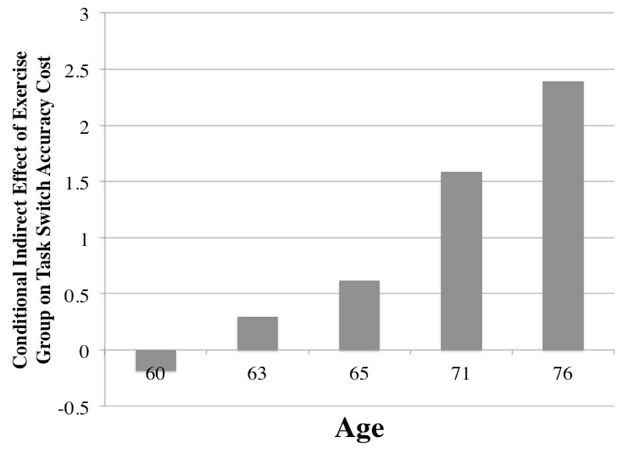

FIGURE 4 | Mediating effect of BDNF within model, as a function of age. Note: Moderated mediation conditional indirect effect. Values of the y-axis are the unstandardized mediating effects (coefficients) of BDNF on the relationship between exercise group and task switch accuracy cost. Bars indicate age quintiles (10th, 25th, 50th, 75th, and 90th percentiles) on the x-axis. Sample distribution is as follows: Age <60: $n = 13$; 61–63: $n = 21$; 64–65: $n = 12$; 66–71: $n = 23$; 71–76: $n = 16$; >77: $n = 7$.

each of these percentiles of age (60, 63, 65, 71, and 76 years), revealing that serum BDNF mediated the relationship between exercise group and task switch accuracy cost only among participants whose ages were in the 75th [$B = 1.714$; CI(SE) 0.260; 5.382 (1.183)] and 90th percentiles [$B = 2.553$; CI(SE) 0.390; 7.807 (1.716)], or 71 years of age and older. Thus, changes in serum BDNF mediated the relationship between exercise group and task performance, specifically for participants aged 71 years and older.

DISCUSSION

In line with our hypotheses, changes in serum BDNF mediated the effect of the exercise intervention on task-switch performance. Interestingly, this effect varied as a function of age such that only individuals older than 71 years of age showed a significant mediating effect of BDNF on task-switch performance. Of note, this relationship is significant in a regression model using baseline task-switch performance as a covariate and when examining change in a RM-ANOVA analysis. These results indicate that moderate-intensity physical activity, such as walking, may be more beneficial to both BDNF and task-switching performance for adults over the age of 70 than younger individuals.

Similar to previous research (Ziegenhorn et al., 2007; Flöel et al., 2010), our results demonstrate that older age was associated with lower BDNF serum levels. However, this relationship was not present after the 1-year intervention for the walking exercise group. Exercise increased BDNF levels, but age moderated this relationship such that older adults in the walking group showed increases in BDNF that their younger exercising group members, nor their stretching control counterparts, displayed. This moderating effect of age may account for heterogeneity in the literature that report negligible associations between longer durations of exercise and BDNF levels in middle-aged adults and in samples with a limited age range (Schulz et al., 2004; Schiffer et al., 2009).

Of particular interest, we found evidence that serum BDNF mediated the association between a 12-month exercise intervention and improvements in executive function, but find that this mediating effect is dependent on the age of the sample. Rodent studies have also reported that BDNF mediates the effects of exercise on cognition and related brain pathways (Van Hoomissen et al., 2004; Vaynman et al., 2004; Hopkins and Bucci, 2010; Gómez-Pinilla and Feng, 2012). Yet, the current study is the first to demonstrate this effect in humans through a randomized controlled trial, and including both serum BDNF and *BDNF* genotype. What makes the current analyses unique is that the mediating effect of BDNF on cognition is independent of *BDNF* genotype, and present only in adults over the age of 70. These results highlight that age-related decreases in serum BDNF may be successfully mitigated by participation in exercise and that this might be a critical mechanism by which exercise improves executive function in late adulthood.

Our results also demonstrate that BDNF mediated the effect of exercise on task-switch accuracy cost, but not on response time, in adults aged 70 years or older. Accuracy on the task-switch paradigm is often interpreted as a measure of executive function ability to execute the task demands, while response times are interpreted as a measure of cognitive control, processing speed or efficiency (Hughes et al., 2013). Thus, our results demonstrate that the effects of exercise on the ability to execute the demands of a challenging task that taps into executive functions are mediated by BDNF in adults over the age of 70. We can only speculate as to the reason for the non-significant effects on response times. One possibility is that there are selective effects of BDNF on the neural correlates that support accuracy verses response times (Hughes et al., 2013). Specifically, BDNF may be mediating the effect of exercise on the prefrontal and parietal regions that support executive function (Jimura et al., 2014) and the "top-down" processing required for task-switch accuracy (Phillips et al., 2013), and not the striatum or regions which are associated with processing speed or response time outcomes (Jimura et al., 2014). Still, our results suggest that the modification in the level of serum BDNF is an important pathway by which exercise influences executive function for adults over 70 years of age.

Despite the strengths of our study, there remain several important limitations. First, analyses and interpretation of the results are based on serum BDNF levels, rather than BDNF directly from brain tissue. Importantly, rodent studies have found significant correlations between cortical BDNF and circulating BDNF levels (Karege et al., 2002), despite controversy on the validity of serum BDNF as a proxy for cortical concentrations (Knaepen et al., 2010). Thus, we believe that this is an acceptable limitation given the obvious challenges of obtaining brain tissue from human subjects. Additionally, while the sample size of each intervention group is similar-to or larger-than previous randomized clinical trials, the statistical models employed in the current analyses limit degrees of freedom and require a large sample to detect effects. It is possible that a larger sample would strengthen current findings or reveal effects in younger ages. Additionally, the current sample was mostly female with little representation of racial minorities, preventing generalization to a population outside of female Caucasians. Finally, our sample was relatively homogeneous without outward signs of cognitive impairment. Therefore, a more varied sample with different demographic characteristics and cognitive abilities may find different results than those described here.

The current findings indicate that adults over the age of 70 may gain the most from aerobic exercise in terms of both serum BDNF and task-switch performance. Indeed, the current sample shows no significant difference in BDNF serum levels or task switch performance at follow-up between the control and exercise intervention groups, however when examined as a function of age, BDNF levels significantly mediate the effect of exercise group on improvements in executive function. The results from this study do not preclude positive effects of exercise on other cognitive domains, other age ranges, other populations, or other putative mechanistic pathways (i.e., inflammatory). These findings highlight the importance of considering both age and BDNF when designing exercise interventions and interpreting the mechanism by which exercise improves cognitive performance, particularly in the elderly.

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A bidirectional relationship between physical activity and executive function in older adults

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Physically active lifestyles contribute to better executive function. However, it is unclear whether high levels of executive function lead people to be more active. This study uses a large sample and multi-wave data to identify whether a reciprocal association exists between physical activity and executive function. Participants were 4555 older adults tracked across four waves of the English Longitudinal Study of Aging. In each wave executive function was assessed using a verbal fluency test and a letter cancelation task and participants reported their physical activity levels. Fixed effects regressions showed that changes in executive function corresponded with changes in physical activity. In longitudinal multilevel models low levels of physical activity led to subsequent declines in executive function. Importantly, poor executive function predicted reductions in physical activity over time. This association was found to be over 50% larger in magnitude than the contribution of physical activity to changes in executive function. This is the first study to identify evidence for a robust bidirectional link between executive function and physical activity in a large sample of older adults tracked over time.

Keywords: physical activity, health behavior, executive function, cognitive ability, longitudinal design

INTRODUCTION

Advancements in medical science in the past century have markedly increased life expectancy but have also heralded a broad set of challenges that accompany an aging population (United Nations, 2011). Age-related cognitive decline is one such challenge, producing wide ranging psychological, social, and economic consequences at both the individual and population level (Frank et al., 2006; Olesen et al., 2012). Emerging evidence suggests that age-related neurocognitive-decline should not be seen as fixed or immutable (Hamer and Chida, 2009). Rather, cognitive function seems to benefit from a healthy lifestyle, most notably from regular physical activity (Hertzog et al., 2009; Ku et al., 2012; Gow, 2013).

This study examines whether engaging in physical activity attenuates declines in higher level cognitive function (executive functioning) over a period of 6 years in older English adults. In addition, the current study investigates the more novel prediction that the relationship between physical activity and cognitive performance is bidirectional, and that executive function will also play a *predictive* role in shaping activity levels over time (Batty et al., 2007; Sabia et al., 2010). The executive functions, in particular, may enable people to consistently engage in effortful behaviors like physical activity in order to achieve long-term health benefits (Hall and Fong, 2007). As the contribution of executive functioning to physical activity has not yet been established in large scale prospective studies, this study also aimed to test this pathway in a sample of more than four thousand older English adults.

PHYSICAL ACTIVITY AS A DETERMINANT OF EXECUTIVE FUNCTIONING

The executive functions are higher level cognitive processes associated with the frontal lobe of the brain that control and coordinate more fundamental processes in the effortful pursuit of goals (Alvarez and Emory, 2006). Complex and multi-faceted in nature, the executive functions include planning, selective attention, sustained attention, the ability to deal flexibly with novel situations, and pre-potent response inhibition (Hall et al., 2008b; Hofmann et al., 2012).

A substantial body of evidence comprising observational studies, randomized controlled trials (RCTs), and meta-analyses, together suggest that physical activity has a substantial beneficial influence on cognitive function, and in particular executive function (Liu-Ambrose et al., 2010; Lowe et al., 2014). A meta-analysis of 18 exercise intervention studies conducted with older adults (aged 55–80) between 1966 and 2001, established that fitness training brings about robust benefits to cognition (Colcombe and Kramer, 2003). Exercisers experienced greater improvements ($g = 0.478$, $SE = 0.029$) in their performance on cognitive function tasks compared to control group participants ($g = 0.164$, $SE = 0.028$). The largest fitness based benefits were associated with improvements in executive processing ($g = 0.68$, $SE = 0.052$). This was a larger effect than was seen for other cognitive processes, namely processes measured using controlled ($g = 0.461$, $SE = 0.035$), spatial ($g = 0.426$, $SE = 0.062$), and speed tasks ($g = 0.274$, $SE = 0.050$). Type of fitness training appeared to influence the magnitude of benefit to cognitive function, with combined strength and aerobic training regimes producing larger effects ($g = 0.59$, $SE = 0.049$) than aerobic training alone ($g = 0.41$, $SE = 0.037$).

More recently a meta-analysis of 29 RCTs examining the effect of aerobic exercise training on neurocognitive performance was conducted. This analysis, including findings from large-scale randomized studies, demonstrated that increases in aerobic exercise were associated with modest but consistent improvements in executive function [$g = 0.123$, (95% CI: 0.021–0.225)] (Smith et al., 2010). This finding suggests markedly weaker effects compared to the meta-analysis of Colcombe and Kramer (2003). Several of the studies reviewed by Smith et al. (2010) included younger adults (e.g., 18–54) than those included in the meta-analysis of Colcombe and Kramer (2003). However, amongst the studies reviewed the age of participants was unrelated to improvements in executive function suggesting that the difference in effect size observed between the two meta-analyses is unlikely to be due to differences in the age composition of the participants included. Interestingly, and in contrast to the finding of Colcombe and Kramer (2003), effects did not differ between studies that included only aerobic exercise and those that included combined exercise programmes. Regards to the quality of the included studies, there were no differences in the effect of exercise on neurocognitive performance based on whether assessors were blinded or not, or whether intention to treat analysis was used or not.

Functional brain imaging studies have shed some light on the brain areas that may mediate the impact of physical activity on executive function (Hillman et al., 2008). When coupled with an RCT design such studies represent a particularly powerful approach to identifying cardiovascular training induced changes in brain function. For instance, a 6-month period of aerobic exercise has been shown to lead to enhanced performance on an attentional control task and greater activation of task-related frontal and parietal brain areas (Colcombe et al., 2004). A recent review of the literature has verified that physical activity appears to be most consistently linked to more efficient patterns of brain activity in frontal and parietal areas during tasks gauging executive function (Voelcker-Rehage and Niemann, 2013).

In addition to the findings from the meta-analyses of experimental studies outlined above, several longitudinal studies have also demonstrated that high levels of physical activity can attenuate declines in cognition (Sofi et al., 2011). In their meta-analysis of 15 prospective studies, Sofi et al. (2011) found that those who performed physical activity at baseline had a significantly reduced risk of cognitive decline during follow-up. Specifically, those who reported a high level of physical activity had a 38% reduced risk of cognitive decline relative to those who reported being sedentary (Hazard Ratio = 0.62, 95% CI: 0.54–0.70). This protective effect was similarly observed for those engaging in low to moderate levels of activity. Funnel plots of effect size vs. standard error suggested no evidence of publication bias. Although this meta-analysis did not discriminate between executive and non-executive measures several additional longitudinal studies point to a potential beneficial influence of physical activity on executive function (e.g., Barnes et al., 2003; Weuve et al., 2004).

Thus, the existing evidence from a broad range of studies shows that physical activity can lead to changes in executive function. An initial aim of the current study was therefore to verify that physical activity can attenuate age-related decline in executive function in a large sample of older English adults. A second aim was to examine dynamic changes in activity levels and executive function to rule out the role of unobserved stable confounders in explaining any association between physical activity and executive function. Specifically, fixed effects multilevel regression analyses were employed to statistically control for the role of non-observed time-invariant characteristics (e.g., sex, birth weight, education, genetic makeup, personality traits) (Allison, 2005). For instance, it is possible that non-observed factors like common genetic variation or childhood factors such as early adversity may underlie both adulthood physical activity and executive function and explain why these variables are interrelated (e.g., Gow et al., 2012). By examining within-person variation such non-observed time-invariant (i.e., factors that do not vary over time, specifically within the time-period of the study) confounders are statistically ruled out.

In contrast to the large number of studies investigating the beneficial effects of physical activity on executive function, very few studies have looked at the opposite possibility, i.e., that executive function facilitates future engagement in physical activity. The current study aimed to examine this possibility using longitudinal analyses in order to establish whether executive function may contribute to beneficial changes in physical activity over time.

EXECUTIVE FUNCTION AS A DETERMINANT OF PHYSICAL ACTIVITY

Participation in physical activity typically requires individuals to effortfully overcome short term costs in return for long term gains. For example, when beginning a new exercise regime, short term costs such as inconvenience and discomfort are initially far more salient than long term (but not immediately apparent) benefits like improved fitness, weight loss and health (Hall and Fong, 2007). Consequently, it has been argued that efficient executive function is essential for both the adoption and maintenance of physical activity (Hall and Fong, 2007; Marteau and Hall, 2013). Executive function can be subdivided in different ways, but key components include volition, planning, purposive action, performance monitoring and inhibition (Lezak, 1995; Stuss and Levine, 2002). The necessity of each of these components for initiating physical activity is readily apparent. To successfully adopt or change physical activity behavior individuals must form a conscious intention about what activity to adopt (volition), identify the sequence of actions required to achieve the intended activity (planning), initiate and maintain focus on the chosen activity over time (purposive action), compare actual progress with planned progress over time, identify and correct mistakes (performance monitoring) and overcome the temptation to remain sedentary (inhibition).

In line with this, research suggests individuals who perform poorly on tests of executive function are less likely to enact physical activity intentions (Hall et al., 2008a,b) and to adhere to regular exercise classes (McAuley et al., 2011). Poor performance on executive function tasks has also been shown to prospectively predict low levels of physical activity and elevated body mass index (BMI) in children (Guxens et al., 2009; Riggs et al., 2010). In a recent study of older women (aged 65–75) changes in executive function over the course of a year where participants engaged in a resistance exercise intervention were positively associated with subsequent exercise adherence over the following year (Best et al., 2014). Whilst this evidence is suggestive of a role of executive function in contributing to physical activity, large scale nationally representative prospective studies have not yet provided evidence that efficient executive function is advantageous in the control of activity behavior, allowing individuals to engage in more physical activity over time relative to others.

THE CURRENT STUDY

The present study investigates the relationship between executive functioning and physical activity measured at four time points over a 6-year period, using data from the English Longitudinal Study of Aging (ELSA) (Marmot et al., 2012).

This study aims to:

(1) Replicate the established association between physical activity and executive function in a large sample of older English adults.
(2) Improve on the analytic strategies used in previous studies by statistically controlling for stable non-observed factors (e.g., genetic factors, birth weight, education, early adversity, etc.) which may underlie both adulthood physical activity and cognitive function and explain why these variables are interrelated.
(3) Test whether physical activity level predicts subsequent changes in executive function.
(4) Test whether the efficiency of cognitive function at one point in time can be used to predict future engagement in physical activity.

METHODS

PARTICIPANTS

The ELSA is a multi-wave longitudinal study of health and quality of life in a large sample of adults aged 50 years or older living in England. The initial ELSA sample was drawn from participants aged 50+ years who took part in the 1998, 1999, and 2000 waves of the Health Survey for England which was designed to represent the English adult population. The first wave of data collection was conducted in 2002 and subsequent waves were carried out every 2 years using both face-to-face interviews/tests and self-completion questionnaires. The sample selection, study design, and measures are described elsewhere (Marmot et al., 2003). Ethical approval for all the ELSA waves was granted from the National Research and Ethics Committee, and all procedures adhered to the Helsinki Declaration. Participants provided informed consent prior to study participation. Data on executive function and physical activity participation were collected in each of the four waves of the study examined as were details of participants' age, gender, education, wealth, and the presence of long-standing illness, as shown in **Table 1**. The analyses in the present study utilized 18,220 observations from 4555 participants who took part in all four study waves.

Table 1 | Descriptive statistics for each wave of the English Longitudinal Study of Aging examined.

Wave (*N*) Parameter	Wave 1 (*N* = 4555) M (SD)/%	Wave 2 (*N* = 4555) M (SD)/%	Wave 3 (*N* = 4555) M (SD)/%	Wave 4 (*N* = 4555) M (SD)/%
Physical activity[a]	3.01 (0.75)	3.03 (0.72)	2.97 (0.75)	2.91 (0.80)
Executive function[b]	10.75 (3.10)	10.59 (3.14)	10.54 (3.22)	10.52 (3.35)
Age	62.34 (9.44)	64.66 (9.46)	66.5 (9.46)	68.62 (9.64)
Female	56.73%	56.73%	56.73%	56.73%
Education[c]	4.33 (2.26)	4.33 (2.26)	4.33 (2.26)	4.33 (2.26)
Log wealth	5.12 (0.66)	5.24 (0.63)	5.28 (0.61)	5.28 (0.63)
Long-standing illness	50.98%	53.17%	53.08%	53.74%

[a] *Frequency of engagement in mild/moderate/vigorous activity, ranging from 1 = hardly ever, or never to 4 = more than once a week.*

[b] *Composite score based on verbal fluency and letter cancelation task.*

[c] *Highest educational qualification, ranging from 1 = no qualification equivalent to 7 = degree or equivalent.*

MEASURES

Physical activity

The physical activity questions were introduced as follows: "*We would like to know the type and amount of physical activity involved in your daily life.*" Participants were then asked three separate questions which gauged how frequently they engaged in sports or activities of (1) mild, (2) moderate, and (3) vigorous intensity. A card was then presented to participants detailing a broad set of typical daily physical activities considered mild (e.g., vacuuming, home repairs), moderate (e.g., walking at a moderate pace, gardening), and vigorous (e.g., running, cycling). The extent to which participants engaged in each type of physical activity was gauged using response options capturing activity levels on a monthly basis coded as follows: 1 = hardly ever, or never; 2 = one to three times a month; 3 = once a week; and 4 = more than once a week. Responses on the three items (mild, moderate, and vigorous activities) were combined to create a composite variable reflecting total physical activity participation. This variable was then standardized so that high scores equate to higher levels of activity, and regression coefficients could be easily interpreted.

As self-reported measures of physical activity may be affected by misreporting or social desirability biases we test whether the ELSA measure correlates with an objective indicator of physical functioning. As part of the ELSA study the time taken for participants to walk a distance of 8 feet at their regular or usual pace was recorded at each wave. The timed walk was completed with the use of a walking aid where necessary (approximately 4% of participants). The timed walk was repeated and the average of the two assessments was calculated. Across 11,711 observations on the study sample the observed correlation between self-reported physical activity and walking speed was 0.42 suggesting a moderate degree of correspondence in the current sample.

Executive function

In each wave participants completed two brief tests of executive function—a verbal fluency task and a letter cancelation task. The verbal fluency task used was a standard, well normed semantic category fluency test (Lezak, 1995; Tombaugh et al., 1999) where participants were asked to generate as many exemplars of a reference category ("animals") as possible in 60 s. Verbal fluency tests, in particular letter fluency tests, are routinely used to assess executive dysfunction (Parker and Crawford, 1992; Phillips, 1997; Henry and Crawford, 2004). Numerous studies have demonstrated that damage to brain regions associated with EF is associated with poor performance on verbal fluency tests (e.g., Baldo and Shimamura, 1998; Schwartz and Baldo, 2001). Patients with frontal lobe damage/executive dysfunction reliably show large deficits in verbal fluency task performance, and importantly, these patients show differential deficits in verbal fluency tasks relative to more general cognitive tests of IQ and processing speed (Henry and Crawford, 2004).

As in the current study, verbal fluency tasks typically present participants with an unusual, unpracticed task (generating words based on specified orthographic criteria), specifying a goal which must be met without giving a strategy for doing so. Performance on verbal fluency tasks requires the successful operation of multiple specific EF processes, including working memory updating (keeping track of responses, keeping the target letter and rules in mind; Henry and Crawford, 2004), self-monitoring of performance, inhibition (of previously given or inappropriate responses) and strategic switching between "clusters" of responses (Hirshorn and Thompson-Schill, 2006). Performance on this animal naming task specifically reflects flexible, goal directed searching of semantic memory, performance monitoring and inhibition of previously named/inappropriate exemplars, and is sensitive to both aging and the beneficial effects of physical activity (Lindwall et al., 2012).

The letter cancelation task asked participants to locate and cross out as many occurrences of the letters P and W as they could on a page printed with 65 randomly ordered letters of the alphabet within 60 s. Letter cancelation tasks assess a key component of executive functioning, selective attention or the ability to focus on relevant stimuli while simultaneously ignoring or screening out irrelevant stimuli (Jurado and Rosselli, 2007; Diamond, 2013). Cancelation tasks also gauge sustained attention, visual search ability and mental speed and have been shown to have high reliability and validity (Uttl and Pilkenton-Taylor, 2001).

The ELSA index of executive function is based on the verbal fluency and letter cancelation tasks. These two tasks form three scales which are summed to produce a composite executive function score (Institute of Fiscal Studies, 2012) ranging from 0 to 20 derived as follows: (1) The number of animals named form a scale from 0 (0–7 animals named) to 8 (30+ animals named), (2) The number of letters reached in the letter cancelation task are recoded into a second scale ranging from 0 (0–174 letters reached) to 7 (450+ letters reached), and (3) The number of target letters missed by the participant in the letter cancelation task is recoded into a scale ranging from 0 (9 or more missed) to 5 (0–1 missed). Executive function index scores were standardized (mean = 0, SD = 1) so that regression coefficients could be interpreted as indicative of change in SD's of a unit change in the independent variable.

Covariates

Details of each participant's age in years, sex, highest educational qualification, non-pension wealth, and whether they had been diagnosed with a long-term illness were used for descriptive purposes and as control variables in the statistical models. The education variable was coded on a seven-point scale ranging from 1 = no qualification to 7 = degree or equivalent. The wealth measure captured a broad set of wealth sources including the value of housing, current and savings account balances, premium bonds, shares, and private debt (e.g., credit card debt and outstanding loans). This variable was log-transformed to reduce skew. The presence of long-standing illness was reported at each wave (present/not present).

STATISTICAL ANALYSIS

Multi-level random coefficient analyses were used to account for the hierarchical structure of the data, whereby non-independent repeated observations across the five waves (Level 1) were nested within participants (Level 2). Our analytic strategy was as follows. First we examined the cross-sectional association between physical activity and executive functioning for individuals (i) across the four waves examined (t). We used multilevel modeling and adjusted for participant age, wealth and the presence of long-standing illness at each wave, as well as unchanging characteristics sex and highest educational qualification. Dummy variables for each wave were included in the analyses (**Model 1**). Using standard notation these regression models can be summarized as follows:

Model 1: Level 1: $\text{Executive function}_{ti} = \beta_{0\text{i}} + \beta_{1\text{i}}(\text{Physical activity}_{ti}) + \beta_{2\text{i}}(\text{Age}_{ti}) + \beta_{3\text{i}}(\text{Wealth}_{ti}) + \beta_{4\text{i}}(\text{Long-standing illness}_{ti}) + \beta_5(\text{Wave}_t) + r_{ti}$
Level 2: $\beta_{0i} = \gamma_{00} + \gamma_{01}(\text{Gender}_i) + \gamma_{02}(\text{Education}_i) + u_{0i}$

Next we examined how changes in physical activity relate to changes in executive functioning by conducting a fixed effects analysis (**Model 2**). This analysis exploits the longitudinal nature of the data to test whether within-person variation in physical activity predicts within-person variation in executive functioning. By examining within-person variation such non-observed time-invariant (i.e., factors such as sex, birth weight, education, genetics, etc. that do not vary over time, specifically within the time-period of the study) confounders are essentially ruled out. The fixed effects analyses adjusted for changes in wealth and health that could explain any association between within-person changes in executive functioning and corresponding changes in physical activity. For example, the difference between a person's executive function level in each participating wave and the person's average level of executive function is represented by "$\text{Executive function}_{ti} - \overline{\text{Executive function}_i}$." This fixed effects multilevel regression analysis eliminates unobservable individual heterogeneity (α) that remains stable across waves, thus producing an account of the executive function–physical activity relation that is free from the influence of important non-observed stable individual factors like genetic variation or experiences of childhood adversity.

Model 2: Level 1: $\text{Executive function}_{ti} - \overline{\text{Executive function}}_{\text{i}} = \beta_{1\text{i}}(\text{Physical activity}_{ti} - \overline{\text{Physical activity}}_{i}) + \beta_{2\text{i}}(\text{Age}_{ti} - \overline{\text{Age}}_{i}) + \beta_{3\text{i}}(\text{Wealth}_{ti} - \overline{\text{Wealth}}_{i}) + \beta_{4\text{i}}(\text{Long-standing illness}_{ti} - \overline{\text{Long standing illness}}_{i}) + \beta_{5}(\text{Wave}_{t}) + (\alpha_i - \overline{\alpha}_i) + (r_{ti} - \overline{r}_i)$

Finally, having identified whether the relationship between executive function and physical activity remains after adjustment for time-invariant factors we tested the direction of this relationship. Using multi-level modeling we investigated whether physical activity in a given wave (t) predicts executive functioning levels in the subsequent wave ($t + 1$) adjusting for the participant's executive functioning score and age at baseline (t) along with gender, education, wealth and health controls (**Model 3**). In **Model 4** longitudinal change in physical activity (from t to $t + 1$) is predicted by executive functioning at baseline (t).

Model 3: Level 1: $\text{Executive function}_{t+1i} = \beta_{0\text{i}} + \beta_{1\text{i}}(\text{Physical activity}_{ti}) + \beta_{2\text{i}}(\text{Executivefunction}_{ti}) + \beta_{3\text{i}}(\text{Age}_{ti}) + \beta_{4\text{i}}(\text{Wealth}_{ti}) + \beta_{5\text{i}}(\text{Long-standing illness}_{ti}) + \beta_{6}(\text{Wave}_{t}) + r_{ti}$
Level 2: $\beta_{0i} = \gamma_{00} + \gamma_{01}(\text{Gender}_i) + \gamma_{02}(\text{Education}_i) + u_{0i}$

Model 4: Level 1: $\text{Physical activity}_{t+1i} = \beta_{0\text{i}} + \beta_{1\text{i}}(\text{Executive function}_{ti}) + \beta_{2\text{i}}(\text{Physical activity}_{ti}) + \beta_{3\text{i}}(\text{Age}_{ti}) + \beta_{4\text{i}}(\text{Wealth}_{ti}) + \beta_{5\text{i}}(\text{Long-standing illness}_{ti}) + \beta_{6}(\text{Wave}_{t}) + r_{ti}$
Level 2: $\beta_{0i} = \gamma_{00} + \gamma_{01}(\text{Gender}_i) + \gamma_{02}(\text{Education}_i) + u_{0i}$

RESULTS

The characteristics of the sample for each of the four waves of ELSA utilized in the study are detailed in **Table 1**. The average age of the sample at baseline was 62.34 years (SD = 9.44) and participants were mainly female (56.7%). Approximately 51% of the sample reported having been diagnosed with a long-standing illness at baseline.

CROSS-SECTIONAL RELATIONSHIP BETWEEN PHYSICAL ACTIVITY AND EXECUTIVE FUNCTION

There was little variation in average levels of physical activity across waves (Min = 2.91, Max = 3.03), as shown in **Table 1**. Executive function scores also varied little across waves, with participants scoring from 10.52 to 10.75 out of 20 on average across the four waves. The correlation between physical activity and executive function appeared to strengthen as participants aged (Overall: $r = 0.23$, $p < 0.001$; Wave 1: $r = 0.17$, $p < 0.001$; Wave 2: $r = 0.20$, $p < 0.001$; Wave 3: $r = 0.25$, $p < 0.001$; Wave 4: $r = 0.30$, $p < 0.001$). Our first multilevel model (**Table 2**) showed that higher levels of physical activity were associated with better executive functioning ($B = 0.05$, $SE = 0.01$; $t = 8.52$, $p < 0.001$) after adjusting for age, gender, education, wealth, and health status. Our analyses indicates that a 1 SD increase in physical activity corresponded with a 0.05 SD increase in executive function scores.

Table 2 | The physical activity and executive function variables were standardized at the wave rather than the full sample level which is more appropriate.

Parameter	Executive function[a]		Executive function[a]	
Model	Random effects		Fixed effects	
	B (SE)	*t*	B (SE)	*t*
Intercept	2.12 (0.12)	18.33**	1.31 (0.14)	9.23**
Physical activity[b]	0.05 (0.01)	8.52**	0.03 (0.01)	4.49**
Age	−0.03 (0.00)	−27.63**	−0.02 (0.01)	−1.87
Female	0.21 (0.02)	9.69**	–	–
Education[c]	0.11 (0.01)	20.63**	–	–
Log wealth	0.08 (0.01)	5.82**	0.03 (0.02)	1.51
Long-standing illness	0.00 (0.01)	−0.34	0.02 (0.01)	1.64
Wave 1[d]	−0.13 (0.01)	−8.58**	−0.03 (0.06)	−0.52
Wave 2[d]	−0.11 (0.01)	−8.70**	−0.05 (0.04)	−1.28
Wave 3[d]	−0.07 (0.01)	−5.50**	−0.03 (0.02)	−1.36

[a] Composite score based on verbal fluency and letter cancelation task.
[b] Frequency of engagement in mild/moderate/vigorous activity, ranging from 1 = hardly ever, or never to 4 = more than once a week.
[c] Highest educational qualification, ranging from 1 = no qualification equivalent to 7 = degree or equivalent.
[d] Base category for analysis of Wave effects is Wave 4.
$^*p < 0.01$, $^{**}p < 0.001$.

FIXED EFFECTS MODEL OF THE PHYSICAL ACTIVITY–EXECUTIVE FUNCTION LINK

Our fixed effects model showed that within-person changes in executive functioning were associated with within-person changes in physical activity levels ($B = 0.03$, $SE = 0.01$; $t = 4.49$, $p < 0.001$). Thus, the relationship between physical activity and executive functioning appeared to be robust to strict statistical control for person-level time-invariant factors. However, approximately 40% of the relationship between physical activity and executive functioning could be attributed to unobserved time-invariant confounding factors. Our fixed effects analyses suggested that an increase of 1 SD in physical activity was associated with approximately a 0.03 SD increase in executive function amongst older adults.

LONGITUDINAL MODELS OF THE DIRECTION OF THE PHYSICAL ACTIVITY-EXECUTIVE FUNCTION LINK

Next, we investigated the direction of the physical activity-executive function relationship using longitudinal random-effects models. We tested the impact of physical activity on subsequent executive functioning adjusting for age, gender, education, wealth, long-standing illness and executive function at baseline. This analysis showed that physical activity is linked to an increase in executive function over time $B = 0.03$, $SE = 0.01$; $t = 5.09$, $p < 0.001$), as shown in **Table 3**.

In the opposite direction we found that high levels of executive function predicted a longitudinal increase in physical activity levels ($B = 0.05$, $SE = 0.01$; $t = 6.54$, $p < 0.001$), while adjusting for age, gender, education, wealth, long-standing illness

Table 3 | The physical activity and executive function variables were standardized at the wave rather than the full sample level which is more appropriate.

Parameter	Executive function ($t + 1$)		Physical Activity ($t + 1$)	
	B (SE)	t	B (SE)	t
Intercept (t)	1.06 (0.08)	13.74**	0.37 (0.09)	4.24**
Physical activity (t)[a]	0.03 (0.01)	5.09**	0.49 (0.01)	65.02**
Executive function (t)[b]	0.59 (0.01)	84.71**	0.05 (0.01)	6.54**
Age (t)	−0.02 (0.00)	−23.18**	−0.01 (0.00)	−14.85**
Female (t)	0.09 (0.01)	6.91**	−0.06 (0.01)	−4.42**
Education (t)[c]	0.04 (0.00)	13.75**	0.02 (0.00)	5.64**
Log wealth (t)	0.03 (0.01)	3.33**	0.10 (0.01)	8.93**
Long-standing illness (t)	−0.05 (0.01)	−4.01**	−0.16 (0.01)	−11.60**
Wave 1[d]	−0.08 (0.02)	−5.36**	0.09 (0.02)	5.36**
Wave 2[d]	−0.03 (0.01)	−2.20*	0.02 (0.02)	1.26

[a] *Frequency of engagement in mild/moderate/vigorous activity, ranging from 1 = hardly ever, or never to 4 = more than once a week.*

[b] *Composite score based on verbal fluency and letter cancelation task.*

[c] *Highest educational qualification, ranging from 1 = no qualification equivalent to 7 = degree or equivalent.*

[d] *Base category for analysis of Wave effects is Wave 3.*

$^*p < 0.01$, $^{**}p < 0.001$.

and physical activity at baseline. A 1 SD increase in executive function was linked to a 0.05 increase in physical activity over time. This increase was found to be equivalent in magnitude to a 2.5 point improvement in education (measured on a seven-point scale ranging from 1 = no qualification to 7 = degree or equivalent) or moving from pass secondary level education to holding a degree. Furthermore, the magnitude of the longitudinal change in physical activity associated with elevated executive function levels was 55% greater than the increase in executive function associated with high levels of physical activity.

DISCUSSION

In a study of more than 4500 adults aged 50+ physical activity and executive function were closely interlinked. This association remained after controlling for demographic and health characteristics. Furthermore, in strictly controlled fixed effects analyses we demonstrated that dynamic within-person changes in executive function corresponded with parallel changes in physical activity. Critically, our analyses showed that the magnitude of the relationship between physical activity and neurocognitive performance appeared to be strongest in the direction from executive function to physical activity. Previously, strong executive abilities have been found to prospectively predict high levels of physical activity in children (Riggs et al., 2010; Pentz and Riggs, 2013) and exercise adherence in older adults (McAuley et al., 2011). The current study suggests that executive abilities may have favorable effects on activity levels at the population level in older adults. This is in line with temporal self-regulation theory (Hall and Fong, 2007) which proposes that pre-potent response inhibition (a key facet of executive functioning) will be essential for the enactment of behaviors like physical activity which require short term effort for long term health gain.

We found evidence that the relationship between physical activity and executive function is bidirectional. Those with poor executive function showed subsequent decreases in their rates of participation in physical activity and older adults who engaged in sports and other activities involving physical exertion tended to retain high levels of executive function over time. This research strengthens and extends existing evidence demonstrating that physical activity can buffer the effects of aging on cognitive decline, particularly in relation to the executive functions (Agrigoroaei and Lachman, 2011; Erickson et al., 2012; Weinstein et al., 2012). This bi-directionality is encouraging from a behavior change standpoint as it suggests that interventions which promote either physical activity or more efficient executive function may have the capacity to produce reciprocal benefits.

Physical activity has been successfully increased among older adults using strategies such as telephone counseling and group-based programmes (Wilcox et al., 2006); pedometer-driven interventions (Talbot et al., 2003); and education-based interventions (van der Bij et al., 2002). Although challenging and labor intensive, there is evidence that executive function can also be improved through training. Lasting improvements in the executive functions have been achieved in older adults using cognitive training techniques and mindfulness meditation (Ball et al., 2002; Willis et al., 2006). As the largest beneficial effects of these cognitive interventions are typically seen in those with the lowest levels of executive function and strong deleterious impulsive tendencies (Hofmann et al., 2012), it may be possible to target interventions at those with the greatest capacity to benefit. However, the extent to which such interventions can enhance engagement in physical activity and whether this could attenuate the declines in physical functioning associated with poor executive functioning (Watson et al., 2010; Koehler et al., 2011) remains to be identified.

Our study has several strengths. Firstly, this is the first study to explicitly investigate the bidirectional nature of the executive function–physical activity relationship over time. The finding that there is a reciprocal, mutually beneficial relationship between the two is of theoretical and practical importance, aiding the interpretation of cross-sectional studies and highlighting new avenues for the design of interventions to facilitate healthy aging. Secondly, the large sample provided precise estimates and high statistical power. Thirdly, our estimates were independent of factors (e.g., wealth, chronic illness) that are known to independently influence engagement in physical activity.

Finally, the use of fixed effects regression techniques allowed us to determine that the executive function–physical activity association is robust to non-observed stable confounding variables. This analysis showed that such non-observed variables explained 40% of the association between executive function and physical activity identified in the standard multilevel regression model. The fixed effects regression results point to the need for non-experimental studies examining the link between executive function and physical activity to either measure or econometrically account for stable potential confounding variables including childhood adversity, genetic endowment and personality traits. Failure to consider these often unobserved variables could lead to inflated estimates of the association between physical activity and executive function. This is because such non-observed variables could lead to changes in both activity levels and executive function and explain why these variables are interrelated.

Fixed effects models using panel or sibling/twin data can appropriately account for childhood adversity or differences in genetic makeup which cannot change. However, fixed effects models cannot fully account for the potential confounding role of personality traits which, although highly stable, have been shown to respond to maturation and life events (e.g., Boyce et al., in press). It may be more appropriate to measure individual differences in personality traits in order to rule out confounding resulting from these variables.

In terms of limitations, the fixed effects regression cannot rule out third variables which are time-varying and not included in the regression model. For instance, if marked changes in health behavior (e.g., increased cigarette or high calorie food consumption) occurred between waves this could negatively impact on both executive function and physical activity levels. Similarly, pronounced changes in health over time may not be adequately captured by the control for chronic conditions included in the analyses. These and other unobserved time-varying variables could account for the association between changes in executive function and physical activity. It is important that future research utilize experimental designs to rule out this potential confounding and to identify whether changes in executive function can causally affect physical activity.

Furthermore, the measure of physical activity used in the ELSA study was participant reported and may have been prone to response bias (e.g., social desirability effects, differential use of response scales). Prior research has shown that the association between objectively recorded and self-reported physical activity is typically modest with several studies showing that both methods share approximately 25% of common variance (e.g., Fahrenberg, 1996; Welk et al., 2004; Nagels et al., 2007). The presence of measurement error is therefore likely to have attenuated the link between executive function and physical activity in the current study (e.g., Celis-Morales et al., 2012).

In the current study we identified a moderate positive association ($r = 0.42$, $p < 0.001$) between the measure of physical activity utilized and a measure of participant walking speed demonstrating that this self-report measure correlates with objective differences in physical functioning. Furthermore, by including analyses of within-person changes in activity levels we can account for individual differences in social desirability bias and in the use of self-report response scales. This is because we examine changes in response so a systematic tendency to over- or underestimate physical activity will be statistically removed. Future research capitalizing on the recent inclusion of accelerometry for the assessment of physical activity in population representative longitudinal studies (e.g., Griffiths et al., 2013) would help verify or challenge the pattern of results identified in the current study.

Due to the constraints of a large-scale multipurpose study such as ELSA the present analyses utilized brief measures of executive functioning (verbal fluency/letter cancelation). While well normed, objective tests, it must be noted that the executive functions are multi-faceted, and comprehensive measurement of executive abilities requires a full neuropsychological test battery. Brief measures such as those utilized in the current study are likely to be less reliable and this measurement error may lead to a downward bias in the size of the effects observed. Similarly, the tasks used will inevitably reflect an element of general cognitive function in addition to "purely" executive functioning, particularly in terms of processing speed. Future studies would ideally explore a broader range of executive abilities to investigate whether particular facets of executive functioning (e.g., planning, sustained attention, self-monitoring) are equally predictive of physical activity.

Finally, whilst our study has shown that relatively strong executive abilities can lead to improvements in activity levels, we were unable to examine the mechanism underlying this change in the current study. Previous research points to the role of the executive functions in allowing intentions to engage in physical activity to be implemented, potentially by inhibiting distractions and facilitating the enactment of behavior (Hall and Fong, 2007). This represents a promising direction for further research (Allan et al., 2010, 2011).

In conclusion, in this large longitudinal study of older English adults we have demonstrated a mutually beneficial, reciprocal relationship between physical activity and executive function that cannot be attributed to either observed or non-observed confounders. Our study suggests that in old age the relationship between executive function and physical activity is dynamic such that changes in executive function can enhance and promote physical activity over time and that changes in activity level can improve future executive function. This finding points to the potentially reciprocal benefits of intervention strategies which aim to concurrently promote executive function and physical activity in older adults.

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Improvements to executive function during exercise training predict maintenance of physical activity over the following year

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Previous studies have shown that exercise training benefits cognitive, neural, and physical health markers in older adults. It is likely that these positive effects will diminish if participants return to sedentary lifestyles following training cessation. Theory posits that that the neurocognitive processes underlying self-regulation, namely executive function (EF), are important to maintaining positive health behaviors. Therefore, we examined whether better EF performance in older women would predict greater adherence to routine physical activity (PA) over 1 year following a 12-month resistance exercise training randomized controlled trial. The study sample consisted of 125 community-dwelling women aged 65–75 years old. Our primary outcome measure was self-reported PA, as measured by the Physical Activity Scale for the Elderly (PASE), assessed on a monthly basis from month 13 to month 25. Executive function was assessed using the Stroop Test at baseline (month 0) and post-training (month 12). Latent growth curve analyses showed that, on average, PA decreased during the follow-up period but at a decelerating rate. Women who made greater improvements to EF during the training period showed better adherence to PA during the 1-year follow-up period ($\beta = -0.36$, $p < 0.05$); this association was unmitigated by the addition of covariates ($\beta = -0.44$, $p < 0.05$). As expected, EF did not predict changes in PA during the training period ($p > 0.10$). Overall, these findings suggest that improving EF plays an important role in whether older women maintain higher levels of PA following exercise training and that this association is only apparent after training when environmental support for PA is low.

Keywords: executive function, aging, physical activity adherence, exercise training, temporal self-regulation theory

INTRODUCTION

Aerobic and resistance exercise training over several months improve cognitive function (Kramer et al., 1999; Colcombe et al., 2004; Cassilhas et al., 2007; Lautenschlager et al., 2008; Liu-Ambrose et al., 2010; Nagamatsu et al., 2012), alter brain function and morphology (Colcombe et al., 2004; Liu-Ambrose et al., 2010, 2012; Voss et al., 2010; Erickson et al., 2011; Nagamatsu et al., 2012), and improve physical fitness (Colcombe et al., 2004; Erickson et al., 2011) and mobility (Nagamatsu et al., 2012) in community-dwelling older adults. It is likely, however, that these positive effects to brain and body will wane over time if older adults return to sedentary lifestyles following training cessation. Indeed, research suggests that adherence to physical activity (PA) decreases following exercise programs. One study reported that only 25% of older men and women continued with aerobic exercise 6 months following a structured 12-month aerobic walking program (Tak et al., 2012), while another showed that only 17% of older women met the walking recommendations (≥150 min per week) 21 months following a 3-month home based walking and balance program (Findorff et al., 2009). Given the decline in PA following exercise programs, it is important to understand why some older adults maintain high levels of PA, whereas others become more sedentary following training.

Temporal self-regulation theory posits that the neurocognitive processes underlying self-regulation are critical to the uptake and maintenance of health-promoting behaviors, including PA (Hall and Fong, 2007; Hall, 2013). These neurocognitive processes are commonly referred to as executive function (EF) and are underpinned by neural networks involving the prefrontal cortex (Shimamura, 2000). There are a variety of EF assessments, but one of the most famous is the Stroop task (Stroop, 1935). The key condition in this task requires individuals to identify aloud the ink color for color words whose name conflicts with the ink color (e.g., the word "blue" is presented in a red font). This condition creates interference that must be overcome because the natural tendency is to identify the word and not the color of the word. Hence, the key aspect of EF recruited on this task is the ability to override a prepotent response in favor of an alternative response. Individuals who perform better on this task (i.e., respond more quickly and/or more accurately) tend to act less impulsively and are better able to resist temptations, as determined by self- and informant-reports (Duckworth and Kern, 2011). They also tend to be more future-oriented, meaning that they discount the value of delayed outcomes *less* than their peers with poorer Stroop performance (Duckworth and Kern, 2011). Additionally, the neural systems associated with Stroop performance (e.g., lateral prefrontal cortices) have been shown to be important to modulating the value of immediate vs. delayed rewards and to avoiding immediate temptations that may have negative long-term consequences (McClure et al., 2004; Shamosh et al., 2008; Hare et al., 2009; Kober et al., 2010).

Although older adults may generally perceive PA to be valuable and health promoting, the costs and barriers associated with PA can be deterrents (Costello et al., 2011). Engaging in PA therefore may require an individual to exert significant effort and to place substantial value on the receipt of positive benefits in the future (e.g., reduced weight, better cardiovascular health) in order to endure immediate costs (e.g., discomfort associated with exertion, opportunity costs related to forgoing sedentary activities) and to overcome barriers (e.g., limited leisure time, lack of nearby recreational facilities). Thus, compared to individuals with lower EF, individuals with higher levels of EF may be more likely to engage in PA routinely because they are better capable of overriding impulses for immediate rewards and of shifting focus to delayed outcomes. This hypothesis follows from the previously mentioned findings that better EF performance is associated with higher levels of self-regulation and to greater future orientation. In thinking about exercise training programs, this association between EF and PA should be especially evident once the structured exercise training has ended, and external support (e.g., encouragement from trainers, incentives for participation) for PA is diminished. At this point, the barriers and costs related to PA increase, and the influence of internal motivational and self-regulatory processes on decisions to engage in PA will likely be important.

The current study is a secondary analysis of a randomized controlled trial (RCT) in which healthy, community-dwelling women (aged 65–75) were randomized to a once-weekly resistance training, twice-weekly resistance training, or twice-weekly balance and tone training, each of which had duration of 52 weeks. We have previously shown that both frequencies of resistance training had a positive impact on executive function, as assessed by change in performance on the Stroop test from baseline to post-training, in comparison to balance and toning (Liu-Ambrose et al., 2010). The current study adds to this previous analysis by examining changes in PA levels over the year following the training program. Using monthly self-reports of PA, the first aim was to characterize the nature of change in PA over the follow-up period. The second and more important aim was to determine whether baseline Stroop performance and/or improvements in Stroop performance over the training period predicted individual variation in PA change over the follow-up period. Beyond the role of EF in temporal self-regulation theory, there are other reasons to examine EF performance in this sample. First, previous research has shown that EF is one domain of cognition sensitive to the positive effects of exercise training (Colcombe and Kramer, 2003; Smith et al., 2010). Second, EF performance has been shown to decline with older age (Jurado and Rosselli, 2007), but within a healthy community-dwelling sample of older women, there is likely substantial variation in EF performance. It was hypothesized that individuals with better performing EF, either at baseline or through improvements acquired during training, would better maintain regular PA over the subsequent year.

MATERIALS AND METHODS

The 52-week training program occurred between May 1, 2007 and April 30, 2008. Details on the participants, study design, and intervention can be found elsewhere (Liu-Ambrose et al., 2010); thus, their presentation is abbreviated below. Ethical approval was obtained from the Vancouver Coastal Health Research Institute and the University of British Columbia's Clinical Research Ethics Board. The RCT was registered at clinicaltrials.gov (Identifier: NCT00426881). Assessors were blinded to the participants' exercise training assignment.

PARTICIPANTS

We recruited and randomized 155 women aged 65–75, who lived in Vancouver, British Columbia. All participants lived independently in the community, had intact cognitive functioning and acceptable visual acuity with or without corrective lenses, and spoke English fluently. Potential participants were excluded if they had a medical condition contraindicating physical exercise, had participated in resistance training in the past 6 months, had a neurodegenerative disease, stroke, or depression, or were receiving estrogen or testosterone therapy. All participants provided written informed consent.

EXERCISE INTERVENTIONS

Resistance training and balance and tone classes were led by certified fitness instructors. Classes were 60 min long, with a 10-min warm-up and 10-min cool-down. The resistance training implemented a progressive, high intensity protocol using Keiser pressurized air system and free weights. Non machine- or weight-based exercises included mini-squats, mini-lunges, and lunge walks. The balance and toning program used stretching, range-of-motion, core-strength, balance, and relaxation exercises. Only body-weight was used, with no additional loading. This group served as a control to factors secondary to study participation, such as dedication to an exercise program and socialization, by matching the twice-weekly resistance training condition for in-person contact.

MEASURES

Executive function

The Stroop Test has three conditions, each containing 80 items. First, participants read out loud color words printed in black ink. Second, participants read out loud the color of colored x's. Finally, participants read out loud the ink color for incongruent color words (e.g., the word "red" is printed in blue ink). The ability to selectively attend to one stimulus property while resolving conflict from competing stimulus properties is calculated by subtracting the amount of time it takes to complete the second condition from the third condition. A smaller time difference indicates better EF, and a greater decrease in the time difference from baseline to post-training indicates greater improvements to EF.

Physical activity (PA)

Self-reported PA was assessed using the Physical Activity for the Elderly (PASE) (Washburn et al., 1993). The PASE consists of 19 items that inquire about different categories of leisure PA. (Note: The PASE also contains 2 items regarding sedentary activity that are not scored). Participants first report the number of days per week the activity was performed over the past 7 days and then the number of hours per day. A summary PA score is computed from weights and frequency values for each of the PA categories. The psychometric properties of the PASE were determined in a sample of 277 adults aged 65–100 years (Washburn et al., 1993). In subsequent studies, PASE scores have been shown to correlate ($r = 0.49$) with objectively measured PA over 3 days via accelerometers (Washburn and Ficker, 1999) and to correlate modestly ($|r| = 0.18 - 0.20$) with objective measures of balance, peak oxygen uptake, and systolic blood pressure (Washburn et al., 1999). In the current study, PASE assessments were conducted in person at baseline (month 0), at training completion (month 12), and at the 1-year follow-up (month 25). During the follow-up period, 13 follow-up PASE assessments were conducted by mail from May 2008 and May 2009. For the final PASE assessment (month 25), the in-person assessment was used unless the participant only completed a final assessment by mail ($n = 6$). The intra-class correlation coefficient, calculated on a subset of the participants ($n = 111$) who had complete PASE data at months 0, 6, 12, and 25, was 0.81, indicating acceptable inter-temporal reliability in the PASE measure across the entire study period.

Covariate variables

Age in years and education level were assessed at baseline by self-report. For education, participants selected the appropriate category, which ranged from "No High School" to "University Degree." The remaining covariates were assessed at baseline and upon training completion (month 12). Depression was assessed by the 15-item Geriatric Depression Scale (GDS) (Yesavage et al., 1982). Weight was assessed in kilograms based on the average of two measurements using a digital scale. Global cognition was assessed using the Montreal Cognitive Assessment (MoCA), which is a 10-min cognitive screening tool containing items related to language, orientation, short-term memory and EF (Nasreddine et al., 2005). The MoCA has a maximum score of 30 points, and scores ≥26 indicate intact cognition (Nasreddine et al., 2005). The number of comorbid conditions related to physical functioning was determined using the Functional Comorbidity Index (FCI) (Groll et al., 2005).

STATISTICAL ANALYSES

Preliminary descriptive statistics, reliability analyses, and logistic regressions were conducted using SPSS version 21 (IBM Corporation, 2012). The main analyses to examine predictors of PA maintenance over the 1-year follow-up were conducted in Mplus version 7.11 (Muthén and Muthén, 2012) using latent growth curve models. For all models, missing data were handled by maximum likelihood estimation under the assumption that missing values were missing at random. To guard against departures from distribution normality, we ran analyses with robust standard errors. We tested model fit by the χ^2 test, comparative fit index (CFI) and the root mean square error of approximation (RMSEA). Good fit is indicated by a non-significant χ^2 test, CFI > 0.95, and RMSEA < 0.05 (Hu and Bentler, 1999).

The first set of growth curve models determined the best-fitting unconditional model (i.e., a model without any predictor variables). The slope factor loading for the initial PASE follow-up assessment (i.e., month 13) was fixed to zero and increased by 0.25 units for each subsequent month, resulting in the final PASE assessment being fixed at 3. By fixing the factor loadings in this fashion, the latent intercept represents the PASE score at month 13, and the slope value represents the amount of change in the PASE score that occurred every 4 months during the follow-up period. Once a satisfactory model was determined, two conditional growth models (i.e., models with predictors) were tested. The first was a base model, which added baseline Stroop performance and the change in Stroop performance over the 12-month intervention as predictors. The second was a covariate-adjusted model, which added additional predictors to determine whether any predictive effects of Stroop performance could be explained by demographic, physical, or psychological variables. Standardize path coefficients (β) are reported for the conditional models.

RESULTS

SAMPLE CHARACTERISTICS

Of the original 155 women who were randomized in one of the three treatment conditions at baseline, 125 (81%) completed ≥2 follow-up PASE assessments and were included in the current study. Logistic regression analyses showed that the participants included in this study did not differ from those who were excluded on baseline demographic or other variables of interest (all $ps > 0.08$). Of the current sample, 57 women (46%) completed the PASE at all follow-up time points, and the rate of completion at any given follow-up time point ranged from 70 to 97%. In a preliminary analysis, we determined that Stroop performance (baseline and change during treatment) did not predict the number of PASE assessments completed during the follow-up period ($ps > 0.55$). **Table 1** provides descriptive statistics for the predictor variables for the study sample. Of note, the average baseline Stroop interference score was 46.30 s ($SD = 19.27$ s), and the average reduction in Stroop interference score from baseline to month 12 was 4.75 s ($SD = 18.38$ s), which represents a significant improvement, $t_{(123)} = -2.81$, $p < 0.01$. **Table 2** shows the bivariate correlations among these variables of interest. Notably, women with better baseline Stroop performance had higher baseline global cognition as assessed by the MoCA ($r = -0.31$). Heavier women at baseline and women with better baseline Stroop performance showed smaller improvements to Stroop performance over the course of the intervention ($r = 0.18$ and -0.64, respectively).

PASE scores decreased steadily from month 13 through month 20 (corresponding to the month of December) and then increased through the spring months (see **Table 3**). Three extreme PASE values were identified (495.10, 842.53, and 908.89) from three

Table 1 | Descriptive statistics for predictor and covariate variables for the study sample and by treatment condition.

		Treatment condition		
Variable	**Total (N = 125)**	**BAT (n = 36)**	**1 × RT (n = 44)**	**2 × RT (n = 45)**
Age (years)	69.54 (2.85)	69.81 (2.92)	69.46 (2.61)	69.42 (3.01)
EDUCATION, NO. (%)				
No high school	1 (0.8)	0 (0.0)	1 (2.3)	0 (0.0)
Some high school	8 (6.4)	2 (5.6)	2 (4.5)	4 (8.9)
Complete high school	20 (16.0)	5 (13.9)	7 (15.9)	8 (17.8)
Trade or professional	23 (18.4)	10 (27.8)	10 (22.7)	3 (6.7)
University certificate	23 (18.4)	5 (13.9)	9 (20.5)	9 (20.0)
University degree	50 (40.0)	14 (38.9)	15 (34.1)	21 (46.7)
PASE, bl	123.57 (59.75)	130.83 (52.33)	117.64 (62.92)	123.57 (61.47)
PASE, Δ	−0.61 (59.50)	−4.43 (57.94)	4.62 (66.91)	−1.49 (51.43)
GDS, bl	0.49 (1.73)	0.22 (1.31)	0.27 (1.03)	0.91 (2.37)
GDS, Δ	0.15 (1.44)	0.38 (1.24)	0.13 (1.04)	0.00 (1.85)
FCI, bl	2.08 (1.61)	2.17 (1.64)	1.84 (1.66)	2.24 (1.51)
FCI, Δ	−0.28 (1.34)	−0.07 (1.24)	−0.34 (1.44)	−0.44 (1.26)
MoCA (max. 30 pts), bl	25.11 (3.00)	25.36 (3.12)	24.73 (3.03)	25.29 (2.83)
MoCA, Δ	−0.31 (3.21)	0.03 (3.26)	0.11 (3.11)	−1.00 (3.15)
Weight, bl (kg)	70.54 (13.83)	69.71 (10.36)	71.45 (15.48)	70.31 (14.47)
Weight, Δ (kg)	−0.34 (3.55)	−1.03 (4.44)	−0.26 (2.83)	0.08 (3.23)
Stroop, bl (s)	46.30 (19.27)	46.36 (14.85)	46.72 (24.72)	46.08 (16.02)
Stroop, Δ (s)	−4.75 (18.38)	−1.98 (17.01)	−6.39 (22.76)	−5.27 (13.70)

Δ, 12-month score minus baseline score; 1 × RT, weekly resistance training condition; 2 × RT, twice weekly resistance training condition; BAT, balance and toning condition; BL, baseline; FCI, functional comorbidity index; GDS, geriatric depression scale; MoCA, montreal cognitive assessment; PASE, physical activity scale for the elderly; Stroop, Stroop interference score measured in seconds.

Table 2 | Bivariate correlations among predictor and covariate variables.

Variable	**1.**	**2.**	**3.**	**4.**	**5.**	**6.**	**7.**	**8.**	**9.**	**10.**	**11.**	**12.**	**13.**	**14.**
1. Age	–	**−0.21**	−0.14	−0.03	0.08	−0.02	0.15	−0.07	0.01	−0.16	0.02	−0.01	0.07	0.06
2. Education		–	0.14	−0.01	−0.03	0.04	0.03	0.02	**0.26**	−0.07	0.01	−0.01	−0.11	−0.07
3. PASE, bl			–	**−0.50**	−0.11	0.06	−0.11	−0.03	0.14	−0.16	**−0.22**	−0.12	−0.06	0.03
4. PASE, Δ				–	0.06	0.05	−0.10	0.12	0.03	0.06	0.02	0.11	0.01	−0.08
5. GDS, bl					–	**−0.54**	0.08	0.16	−0.07	0.08	**0.25**	0.13	0.03	−0.01
6. GDS, Δ						–	0.07	0.06	0.03	−0.05	0.02	−0.04	0.01	−0.02
7. FCI, bl							–	**−0.49**	0.06	−0.17	**0.25**	−0.01	−0.01	0.14
8. FCI, Δ								–	−0.08	0.15	**−0.22**	0.14	0.16	−0.22
9. MoCA, bl									–	**−0.54**	0.13	−0.01	**−0.31**	0.16
10. MoCA, Δ										–	−0.08	0.04	0.14	−0.13
11. Weight, bl											–	−0.07	−0.04	**0.18**
12. Weight, Δ												–	0.03	0.04
13. Stroop, bl													–	**−0.64**
14. Stroop, Δ														–

N = 125. Pearson product-moment correlations are presented except those involving education, which are Spearman's rho. Significant correlations are noted in bold font, p < 0.05. Δ, 12-month score minus baseline score; BL, baseline; FCI, functional comorbidity index; GDS, geriatric depression scale; MoCA, montreal cognitive assessment; PASE, physical activity scale for the elderly; Stroop, stroop interference score measured in seconds.

distinct individuals that were outliers (>3 *SD*s above mean) both relative to the scores of the sample at that time point and relative to the individual's scores at other time points. These values were removed from the estimation of the growth models.

UNCONDITIONAL GROWTH MODELS

Three variations of the unconditional growth model were considered to characterize the change in the PASE follow-up scores over time (see **Table 4**). A model with both linear (i.e., time) and quadratic (i.e., time^2) slope factors (model B) provided better fit

Table 3 | Means (standard deviations) and number of assessment completers for PASE scores over the 1-year follow-up.

Month 13	Month 14	Month 15	Month 16	Month 17	Month 18	Month 19
143.37 (60.42) $n = 105$	134.44 (62.36) $n = 102$	133.45 (62.87) $n = 105$	133.87 (62.43) $n = 105$	137.61 (68.34) $n = 100$	128.50 (65.31) $n = 101$	122.10 (55.38) $n = 100$
Month 20	**Month 21**	**Month 22**	**Month 23**	**Month 24**	**Month 25**	
101.15 (55.26) $n = 99$	113.62 (54.91) $n = 91$	122.55 (55.96) $n = 88$	120.38 (54.79) $n = 90$	125.68 (54.24) $n = 94$	123.78 (58.94) $n = 114$	

Table 4 | Determination of best-fitting unconditional growth curve model.

	Fit statistics				Intercept		Linear slope (Time)		Quadratic slope (Time^2)	
Model	**χ^2 (*df*)**	**BIC**	**RMSEA**	**CFI**	**Mean**	**Var.**	**Mean**	**Var.**	**Mean**	**Var.**
A. Linear	122.98** (86)	13421.94	0.059	0.945	136.49***	2537.99***	−6.53***	85.76*	–	–
B. Quadratic	101.85 (82)	13414.36	0.045	0.971	145.70***	2198.22***	−26.80***	132.45	6.54***	17.13
C. Quadratic	104.09 (85)	13403.05	0.043	0.972	145.62***	2513.89***	−26.88***	85.26*	6.60***	0.00

df, degrees of freedom; BIC, bayesian information criteria; CFI, comparative fit index; RMSEA, root mean square error of approximation; Var., variance. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

than a model with only a linear slope factor (model A); however, in this quadratic model, the variances of the slope factors were not significant. Because the linear slope variance had been significant in model A, the variance for the higher-order quadratic slope was fixed to zero to produce model C, which resulted in significant variance in the linear slope. This model was chosen as the basis for the main analyses due to its superior model fit statistics compared to models A and B (Duncan et al., 2006; Muthen et al., 2011)[1]. The negative linear slope ($B = -26.88$) indicates that PA decreased over time; however, the positive quadratic slope ($B = 6.60$) indicates that this negative trend decelerated and reversed course before the end of follow-up year. **Figure 1** displays each individual PASE trajectory (colored lines) along with the average trajectory (black line) specified by model C. The figure shows the substantial variation in PASE scores across time points. It also shows the quadratic effect—the black line begins to bend upward during the second-half of the follow-up period.

CONDITIONAL GROWTH MODELS

Because the quadratic slope variance was fixed to zero (indicating no heterogeneity in the rate of deceleration), the conditional growth curve models could only examine whether the baseline and change variables predicted individual differences in the PASE intercept and linear slope. The base conditional growth model (see left-hand columns of **Table 5**) had good fit based on a non-significant χ^2, RMSEA < 0.05, and CFI > 0.95. In this model, women who showed greater improvements in Stroop performance reported greater maintenance of PA over the subsequent one-year follow-up period ($\beta = -0.36$, $p < 0.05$, see **Figure 2**). This model explained nearly 20% of the variance in the PASE slope but essentially none of the PASE intercept variance. An adjusted model was created to determine whether this predictive effect held when accounting for several important covariates theoretically related to EF and PA maintenance. These included baseline age and education, treatment condition, and baseline and change scores for the following variables: FCI, PASE, MoCA, GDS, and weight. In this adjusted model, the predictive effect of Stroop interference change on the PASE linear slope remained significant ($\beta = -0.44$, $p < 0.05$, right-hand columns of **Table 5**). Additionally, greater baseline PASE scores and greater increases in PASE scores over the intervention period predicted higher PASE intercepts ($\beta = 0.89$ and 0.68, respectively, ps < 0.001), and higher baseline global cognition (as indicated by higher MoCA scores) predicted lower PASE intercepts ($\beta = 0.28$, $p = 0.001$). Moreover, higher baseline depression and greater increases in depression over the intervention predicted greater decreases in the PASE linear slope ($\beta = -0.50$, $p = 0.01$ and $\beta = -0.32$, $p < 0.05$, respectively). This covariate-adjusted model explained over 75% of the variance in the PASE intercept and 50% of the variance in the PASE slope.

In light of the fact that we had previously found that both resistance training conditions benefited Stroop performance in this sample (Liu-Ambrose et al., 2010), we tested whether there was a significant indirect effect of resistance training on PA adherence through changes in Stroop performance. Using the model indirect command in Mplus 7.11 and bootstrapped 95% confidence intervals (5000 bootstrap resamples), we found no evidence for an indirect effect, either for once-weekly resistance training ($\beta = 0.04$ [-0.05, 0.13]) or twice-weekly resistance training ($\beta = 0.03$ [-0.06, 0.13]). The possibility that Stroop performance mediated the effects of resistance training on PA adherence was further undermined by the fact that neither

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[1] In secondary analyses, we determined that using model A as the basis for the conditional growth curve models provided very similar results to those reported in the text using model C. In both the base and covariate-adjusted models, change in Stroop performance predicted maintenance of physical activity over the 1-year follow-up period, $\beta = -0.35$, $p = 0.046$ and $\beta = -0.44$, $p = 0.036$, respectively.

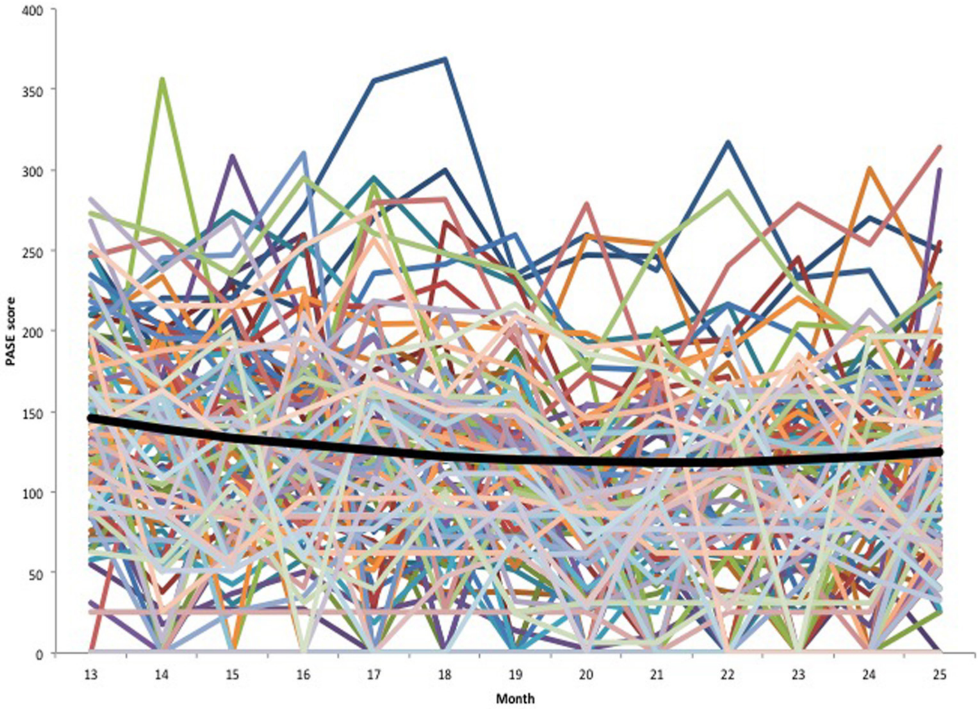

FIGURE 1 | Unconditional growth model. Individual growth trajectories are indicated by the colored lines. The average growth trajectory specified by Model C in **Table 4** is indicated by the thicker black line.

Table 5 | Conditional growth curve models predicting PASE intercept and slope over 1-year follow-up period.

	Base model				**Covariate-adjusted model**[a]			
	Outcome: PASE intercept		**Outcome: PASE linear slope**		**Outcome: PASE intercept**		**Outcome: PASE linear slope**	
	β	***p* value**	**β**	***p* value**	**β**	***p* value**	**β**	***p* value**
PREDICTOR								
PASE intercept	–	–	−0.340*	0.016	–	–	−0.102	0.815
Stroop, baseline	−0.038	0.744	−0.150	0.401	0.053	0.493	−0.237	0.275
Stroop, Δ	−0.003	0.983	−0.355*	0.043	0.145	0.101	−0.441*	0.033
Explained variance	$R^2 = 0.001$		$R^2 = 0.198$		$R^2 = 0.756$		$R^2 = 0.503$	
MODEL FIT INDICES								
Chi−square test	$\chi^2(107) = 131.90$, $p = 0.052$				$\chi^2(323) = 451.72$, $p < 0.01$			
RMSEA (90% CI)	0.043 (0.000, 0.066)				0.057 (0.044, 0.069)			
CFI	0.970				0.900			
BIC	14,440.945				17,843.098			

Maximum likelihood estimation with robust standard errors, N = 125. Standardized estimates (β) are presented. Δ, 12-month score minus baseline score; BIC, bayesian information criteria; CFI, comparative fit index; RMSEA, root mean square error of approximation. *$^*p < 0.05$.*

[a] *In addition to the variables listed, this model also includes baseline age and education, treatment condition, and baseline and change scores for the following variables: Functional Comorbidity Index, Geriatric Depression Scale, Montreal Cognitive Assessment, Weight (kgs), and Physical Activity Scale for the Elderly.*

once-weekly nor twice-weekly resistance training, in comparison to BAT, predicted PA adherence over the follow-up period (*ps* > 0.70).

Finally, we tested the hypothesis that the association between EF and PA adherence during the resistance-training period would be weak, perhaps because external support for PA would overshadow the influence of internal self-regulatory processes on PA. Path analysis revealed that the sign of the coefficients were negative (as expected), but neither baseline Stroop performance ($\beta = -0.04$, $p = 0.56$) nor change in Stroop performance ($\beta = -0.13$, $p = 0.16$) predicted change in PA during the training period. Furthermore, neither baseline nor change in Stroop performance predicted the number of classes attended during the 12-month training phase (*ps* > 0.40).

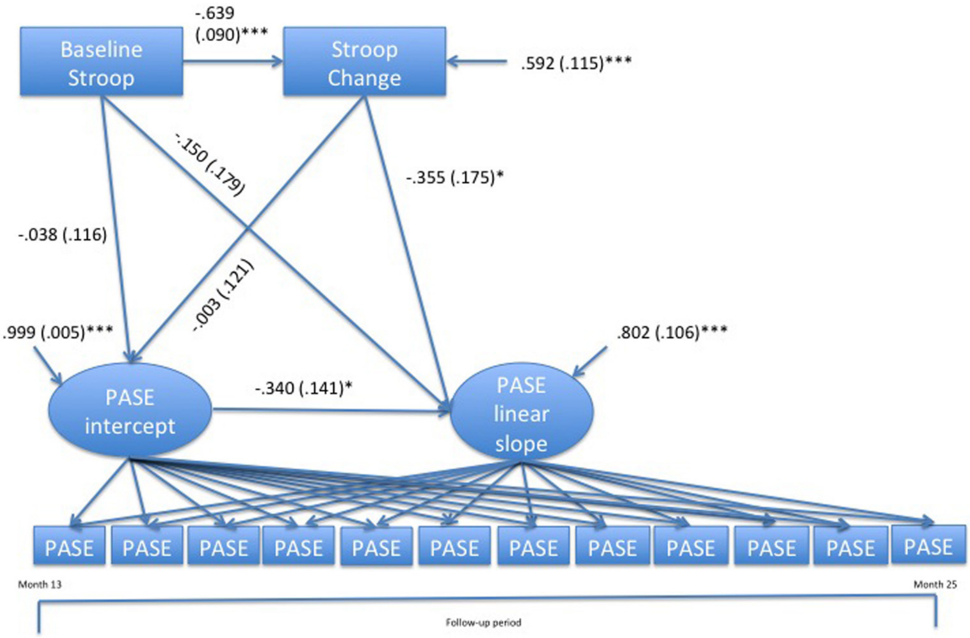

FIGURE 2 | Conditional growth curve model of the predictive effects of change in Stroop performance during the intervention on physical activity during the 1-year follow-up period. Standardized path coefficients (standard errors) and standardized residual variances (standard errors) are shown. To simplify the depiction of the model, the PASE quadratic slope factor, the slope and intercept factor loadings, and the residual variances for PASE indicator variables have been omitted. $^{*}p < 0.05$. $^{***}p < 0.001$.

DISCUSSION

Motivated by temporal self-regulation theory (Hall, 2013), the current study tested whether individual differences in EF influence adherence to PA after completing a structured year-long exercise training program (either resistance training or balance and toning). Our results show that individuals who made greater improvements in EF during the training period showed better adherence to PA over the following year. Importantly, these findings could not be accounted for by changes in other variables, including global cognition, PA during the training period, functional comorbidity, or depression. This suggests a specific role for a key aspect of EF—namely inhibition of prepotent responses—in maintaining health-promoting behavior.

Previous studies have demonstrated the utility of temporal self-regulation theory in explaining individual differences in health outcomes in various populations (Hall and Fong, 2010). For example, Hall et al. (2006) found that better Stroop performance was related cross-sectionally to lower smoking rates, less alcohol consumption, and to better sleep quality in a community sample spanning 20–100 years of age. In another study, Hall et al. (2010) found that higher EF performance predicted a greater likelihood of survival over a 10-year period among community-dwelling older adults suffering from one or more chronic illnesses. Finally, it has been shown that overweight and obese children with a greater valuation of delayed monetary and food rewards, relative to immediate rewards, show improved weight loss (Best et al., 2012). Together, these studies suggest that exerting top-down control and valuing delayed outcomes are important predictors of positive health behaviors and outcomes.

Based on past studies alone, in which EF was only assessed at a single time point, one could not rule out that the researchers were assessing a stable individual factor that could not be altered. Thus, the most interesting contribution of the current study to temporal self-regulation theory is to show that improvements to EF predict positive health behavior adherence. Naturally, the question turns to what sorts of intervention strategies can be used to further improve EF, beyond the resistance and aerobic exercise training strategies shown to be effective in aging populations. Cognitive training has received substantial attention in recent years, and there is some evidence that training programs focused on various cognitive domains improve the targeted domain and may transfer to novel tasks in older adults (Ball et al., 2002; Willis et al., 2006; Anguera et al., 2013). There is intriguing, though tentative, evidence that training specific EF components (e.g., working memory, inhibitory control) may be especially useful in the context of improving health behavior. For example, working memory training has been shown to reduce alcohol consumption in problem drinkers (Houben et al., 2011), and inhibitory control training has been shown to reduce chocolate consumption among chocolate lovers (Houben and Jansen, 2011). Another strategy involves training individuals to engage in mental time travel in order to enhance the vividness of future outcomes; this strategy has been shown to reduce *ad libitum* energy intake in a laboratory setting (Daniel et al., 2013). Whether such strategies, either EF training or mental time travel, could improve health behavior in older adults is unknown.

It is noteworthy that change in EF, but not baseline EF, predicted PA adherence. Temporal self-regulation theory would suggest that both should be important predictors. It may be that change in EF was more sensitive in the current study because of the closer temporal proximity with the assessment of PA adherence. That is, the change in EF may provide a more accurate reflection of each person's EF performance at the time of training cessation than would the baseline assessment. It is also possible that the improvements in EF we observed may partially reflect changes in other processes during the intervention that may also be important to PA adherence. This seems unlikely given that changes in EF did not correlate with changes in any other variable studied, including change in reported PA during the intervention period (see **Table 2**), and that the predictive effects were unaltered in the covariate-adjusted model.

Another important contribution to temporal self-regulation theory is our result that the relationship between EF and PA adherence was not apparent during the training phase of the study. This null effect was expected because during this phase external support for PA was substantial. As examples, participants received newsletters featuring personal accomplishments, follow-up contacts when missing 2 consecutive classes without a reason, and support for overcoming barriers to participation. It is likely that the external environment modulates the influence of internal neurocognitive processes on health outcomes (Hall and Fong, 2007; Best et al., 2012; Hall, 2013), which points to additional strategies to promote health behavior. Although resource constraints would likely prevent exercise training programs to continue indefinitely, a gradual reduction in support from exercise trainers and other staff may help individuals adhere to PA. Periodic booster sessions may also help by ensuring that older adults are receiving help in overcoming barriers to PA. As our results suggest, this external support may be especially important for those individuals who do not make significant improvements in EF during the formal training period.

We also found that higher levels of baseline depression, as well as increases in depression over the training period, predicted greater decreases in PA over the follow-up period. This finding comports with the conclusion of a systematic review finding that depression is a significant risk factor for subsequent diminished PA (Roshanaei-Moghaddam et al., 2009). As the authors of that study note, depressed individuals may have lower motivation and energy levels, thus leading to a preference for sedentary activity. Together with our main results, this suggests important and distinct roles of emotional and motivational functioning, on the one hand, and self-regulatory functioning, on the other hand, in determining changes in PA over time.

There are noteworthy limitations to this study. Our study sample was fairly homogenous, as it consisted exclusively of independent community-dwelling older women who were free of major physical or cognitive impairments. This limits the generalizability of these findings to other populations. Another limitation is that we used a self-report measure of PA rather than an objective, accelerometry-based measure. Thus, our measures may be affected by many of the issues and biases associated with self-report, including cognitive limitations (e.g., inaccurate recall) and social desirability. However, by including numerous assessments ($n = 13$) of PA over the follow-up period, we believe that these data provide an accurate picture of how PA changed over that period, even in light of these issues related to self-report.

To conclude, our findings suggest an important role of cognitive plasticity during aging by showing that older women who make greater improvements to EF during an exercise training program (either resistance training or balance and toning) are more likely to adhere to PA over the following year. Our results also suggest a moderating role of environmental support, and therefore, highlight the importance of considering external environmental factors in conjunction with internal self-regulatory processes when determining optimal strategies for promoting positive health behavior.

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Executive function and self-regulated exergaming adherence among older adults

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The rise in dementia and the evidence of cognitive benefits of exercise for the older adult population together make salient the research into variables affecting cognitive benefit and exercise behavior. One promising avenue for increasing exercise participation has been the introduction of exergaming, a type of exercise that works in combination with virtual reality to enhance both the exercise experience and health outcomes. Past research has revealed that executive function (EF) was related to greater use of self-regulatory strategies, which in turn was related to greater adherence to exercise following an intervention (McAuley et al., 2011). Best et al. (2014) found improvement in EF related to adherence to exercise post- intervention. Anderson-Hanley et al. (2012) found that for older adults aerobic exergaming yielded greater cognitive benefit than traditional exercise alone; however, questions remain as to the possible impact of greater cognitive benefit and other factors on participants' involvement in exercise following the end of an intervention. The current study presents follow-up data exploring the relationship between EF, self-regulation, and exercise behavior in the post-intervention (naturalistic) period. Herein, it was predicted that higher EF at the start of the naturalistic window, would predict subsequent exercise with an exergame. Contrary to expectations, results suggest that those with poorer EF are likely to exergame more frequently. The results of this study contradict previous literature, but suggest an interesting relationship between EF, self-regulation, and exercise behaviors when exergaming is employed, particularly with older adults with some cognitive decline. We hypothesize that other factors may be at work, perhaps expectation of cognitive benefit might act as a unique motivator.

Keywords: exergame, aerobic exercise, cognition, older adults, self-regulation, executive function

INTRODUCTION

The positive impact of exercise on cognition has been well documented in the scientific literature (Kramer et al., 1999; Colcombe et al., 2004; Hogan et al., 2013). Longitudinal research in Europe indicated that people aged 50 years and older who participated in any kind of physical activity showed less cognitive decline after 2.5 years than those who performed no physical activity (Aichberger et al., 2010). Randomized controlled trials (RCTs) and exercise intervention studies, moreover, have revealed that both aerobic exercise (Colcombe and Kramer, 2003; Smith et al., 2010) and resistance training (Cassilhas et al., 2007; Liu-Ambrose et al., 2010; Nagamatsu et al., 2012) improve cognition, especially aspects of executive function (EF) including planning, decision making, and inhibition. Nonetheless, research reveals that only 4% of adults exercise at the recommended frequency and intensity (Gordon-Larsen et al., 2004).

Given the well-established evidence-base suggesting that exercise offers cognitive benefit for the older adult population in particular (Colcombe et al., 2004; Hindin and Zelinski, 2012), and the concomitant rise in rates of dementia (Steffens et al., 2009), research efforts must now turn to understanding variables which may predict this populations' participation in and adherence to a fitness regimen. An understanding of the variables that predict involvement in exercise behavior (both during and after prescribed interventions) could lead to more targeted interventions for older adults and, therefore, to more exercise and cognitive benefit.

Various theoretical approaches have evolved that attempt to understand behavioral constructs and related variables that may moderate the relationship between exercise intervention and maintenance of exercise behavior. While our research on the cognitive benefits of exercise for older adults led us to examine factors related to adherence within that context, it is important to note that significant contributions to the work on the role of EF in exercise adherence has resulted from a broader set of research. That body of literature has pioneered the role of EF in self-regulation and examined that relationship in diverse topics ranging from health behaviors and consumer research on decision making, lending further support to the notion that EF plays a critical role in the maintenance of desirable behaviors (e.g., in treatment of substance abuse, in pain management, recovery from brain injury; Solberg Nes et al., 2009; Hofmann et al., 2008; Hunt et al., 2013; Bickel et al., 2014). Generally, EF is the mechanism that allows a person to make choices about behaviors that may not immediately positively affect them, but will have positive effects in the long run (e.g., suppressing an unconsidered impulse to buy something expensive, going to the gym daily to make incremental steps toward health). Executive function requires a host of underlying cognitive, biological, and social processes to function (Hall and Fong, 2007). It is hypothesized that EF may play a major role in various behaviors, but especially self-motivated exercise behaviors, because it is implicated in the delay of gratification and participation in activities which may not yield immediate external reward (Hall and Fong, 2007).

One approach, the so-called social-cognitive approach, is undergirded and perpetuated by findings that variables like self-efficacy and social support (Chogahara et al., 1998; McAuley and Blissmer, 2000) may be mechanisms through which exercise behaviors occur in the absence of other extrinsic motivations (e.g., rewards for participating in employer health and wellness program). A variant of those theories cited in the social and health psychology literature, the Theory of Planned Behavior (TBP), has been suggested to play a role in health-related behaviors (Godin and Kok, 1996). The theory attempts to explain how people's attitudes and beliefs about objects and themselves influence their participation in health-relevant behaviors (Ajzen, 1985). Self-efficacy is a core control belief in the TBP model and has been robustly demonstrated to play a role in people's engagement in exercise behaviors.

Another approach to analyzing maintenance of exercise behavior post-exercise intervention is a more biological approach that has been motivated by existent evidence suggesting that exercise structurally and functionally alters the brain (Colcombe et al., 2006; Hillman et al., 2008). Research from this neurocognitive approach focuses, in particular, on the role of top-down processes, including EF in adherence to exercise behaviors. The temporal self-regulation theory (TST), a theory of the neurocognitive approach, provides a theoretical framework through which exercise intervention, EF, and regimen adherence may relate. Generally, TST offers an explanation for how people decide to engage in immediate behaviors that yield later, but not immediate, effects. According to TST, there are many underlying social, biological, and cognitive processes that work together to enable a person to engage in behaviors that will produce delayed benefits; these processes are crucial for the motivation required to continue a regular exercise regimen (Hall and Fong, 2007).

In a recent RCT and subsequent follow-up study of these phenomena, Best et al. (2014) examined the relationship between EF and adherence to an exercise routine post-fitness intervention. The researchers hypothesized that increased EF (due to an exercise intervention) would predict continued participation in exercise once the intervention ceased. Results revealed that women who had experienced greater EF benefit from the exercise intervention were more likely to adhere to an exercise routine in the year following the cessation of the intervention. These results were unaffected by any potential covariates (i.e., age, education, depression, and MOCA scores). Best et al. (2014) research suggests that functional changes in brain processes, especially EF, may subsequently impact maintenance of exercise behavior.

McAuley et al. (2011) conducted a year-long exercise intervention with a sample of older adults and subsequently analyzed exercise behaviors in the year following the intervention. Expanding on prior research and connecting aspects of the social-cognitive approach with the neurocognitive approach, they included various measures of EF, such as working memory, inhibition, and task switching, while also measuring the use of self-regulatory strategies and self-efficacy. The results revealed that specific types of EF (i.e., task switching and inhibition) were related to greater use of self-regulatory strategies, which in turn was related to higher self-efficacy; this higher self-efficacy predicted greater adherence to an exercise routine in the year following the cessation of the exercise intervention. McAuley et al. (2011) research is especially important for understanding health-related behaviors, because it suggests that both social/personal characteristics and neurocognitive processes play a role in the maintenance of healthful behavior, such that self-efficacy may mediate elements of EF to influence exercise behavior.

The current research aims to expand on research such as Best et al. (2014) and McAuley et al. (2011) by examining how change in EF relates to and plays an important role in exercise adherence. The question investigated in the current research is whether or not EF may be related to people's participation in an exercise behavior; in particular, after the conclusion of a prescriptive exercise intervention period. In our previous research we examined the impact of exergaming ("cybercycling"[1]) on cognitive functions in older adults (Anderson-Hanley et al., 2012). Exergaming is a type of exercise that works in combination with virtual reality and/or videogames to enhance both the exercise experience and possibly also relevant mental processes (e.g., Wii Fit and X-Box Kinect) and is a promising avenue for increasing exercise participation. We found that exergaming yielded greater cognitive benefit, specifically EF, than riding a stationary bike alone (despite a similar dose of exercise in terms of miles, minutes, and intensity). Crucial questions remain, however, as to the possible impact of such a cognitive benefit and other relevant factors on participants' involvement in exercise behaviors following the end of the exergaming intervention. The current research is a follow-up study which further explores the relationship between exercise behavior, self-regulation and executive control in the post-intervention period of the above noted cybercycle study.

HYPOTHESIS

As demonstrated by prior research (McAuley et al., 2011; Best et al., 2014), it was predicted that EF at the start of the naturalistic exercise window (thus at the end of the cybercycle randomized

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[1] stationary bike with a virtual reality screen that displays interactive bike tours with on-screen competition or a videogame.

trial), would predict frequency of exercise on the cybercycle post-intervention.

METHODS

SAMPLE CHARACTERISTICS

In a previous randomized clinical trial, 102 older adults were recruited from local independent living facilities and randomized to one of two exercise conditions: physical exercise alone (traditional stationary bike) vs. interactive virtual reality-enhanced stationary cycling (cybercycle). Individuals with known neurological disorders (e.g., Alzheimer's disease) or significant functional disabilities that would restrict participation in physical exercise or cognitive testing were excluded from participation; written physician approval to exercise was required. The study was approved by a human subjects review committee and written informed consent was obtained for all enrollees; the study was registered as a national clinical trial[2] (NCT01167400). Sixty-three participants completed the 3-month randomized portion of the study (results reported elsewhere; see Anderson-Hanley et al., 2012), and 51 were willing and able to continue exercising during the subsequent naturalistic exercise period and reported for final testing after that 6-month window. The average age of the group that participated during the naturalistic window ($n = 51$) was 79.0 years (SD = 8.4) and their average years of education was 13.7 (SD = 2.5); 71% were women and the sample was predominantly Caucasian (>90%). Data from 30 participants were in the present analyses; they include those who had also completed the RCT, completed evaluations at the end of the naturalistic exercise window, had data on the variables of interest herein, and had valid exercise data (those with zero ride frequency who had a physical injury or had moved away were dropped from the analyses). Outliers were also examined and consistent with Best et al. (2014), results are also presented with one outlier removed.

PROCEDURES

During the RCT, participants were randomly assigned to either the traditional stationary bike group or the cybercycle group. Participants in both groups rode the same recumbent stationary bike, but in the cybercycle condition a virtual reality screen was active and participants interacted with a virtual bike tour, steering and competing with avatars. All participants were encouraged to gradually increase their total time of exercise to 45 min, 5 days a week in their respective condition, consistent with American College of Sport Medicine (ACSM) standards (Garber et al., 2011). Participants were instructed to adhere to their assigned exercise condition for 3 months. After each exercise session participants documented their ride behaviors on a paper log. Ride logs were collected from the study sites and used to calculate ride statistics (frequency, intensity, duration). The average number of rides for the cybercycle group and control groups were 51.3 (SD = 3.32) and 53.3 (SD = 3.14), with average durations of 35.5 min and 33.8 min, respectively. After 3 months in their randomized conditions, participants were invited to engage in naturalistic exercise for 6 months.

During the naturalistic exercise window, participants in both the control and cybercycle conditions were encouraged to exercise 5 days a week for 45 min per session while using the cybercycle in its fullest capacity (e.g., navigating various bike tours or playing a dragon chase videogame). It is the naturalistic exercise window that is the focus of this report. Again, paper ride logs were collected from the study sites and used to calculate ride statistics as noted above. We chose to focus on the middle 3 months of the 6-month ride window due to missing data from some sites at the beginning and end of the naturalistic window. Using a 3-month window also provided a comparable exercise window to that studied in the RCT.

MEASURES

Tests of cognitive functioning were administered at enrollment (baseline), 1 month after that (pre-intervention), and then again after the 3-month randomized exercise conditions (post-intervention/pre-naturalistic exercise window). The current research examines the relationship between EF post-intervention and exercise behavior during the follow-up naturalistic window, during which participants were encouraged to utilize the cybercycle in its full capacity.

Executive function

The original study utilized a full battery of neuropsychological tests to characterize the sample and track changes; alternate forms were used at each time point. Consistent with recent data published on this topic (Best et al., 2014), the current analysis focused on the Stroop Test (Stroop, 1935). The Stroop Test has proven to be one of the most effective measures of EF as the brain areas activated during this task are associated with cost-benefit decision making and impulse control (Strauss et al., 2006). A shortened, 40-item version of the Stroop was used, presenting colored blocks first (Stroop A), followed by black text color names (Stroop B), and finally color names printed in contrasting colored ink (Stroop C; adapted from Van der Elst et al., 2006). In an effort to partially replicate the recently reported work of Best et al. (2014), Stroop C—Stroop A was used as a measure of EF, and it was the change in this EF variable over the course of the initial RCT that was the focus of our analyses. Given that that time in seconds is the outcome, greater Stroop C-A scores indicate worse EF; thus, a negative change score (post-RCT minus pre-RCT), indicates improving EF.

Exercise attitudes measures

In addition to cognition, other variables were measured to examine possible influences on exercise behaviors; in particular: self-efficacy, perceived benefits and barriers to physical activity, and attitudes and motivations towards physical activity and the cybercycle specifically. Self-efficacy was measured using the Self Efficacy for Physical Activity Survey (SEPAS; Sallis et al., 1988); questions assessed how confident participants were that they could complete exercise behavior in the face of various barriers such as needing to wake up early, set aside time, and continue adhering to a routine during stressful times. The Exercise Benefits/Barriers Scale (EBBS; Sechrist et al., 1987) was used to measure the degree to which participants saw both benefits and barriers in exercise. Questions

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assessed whether participants thought exercise would benefit variables such as their physical and mental health and whether participants perceived a number of barriers, such as embarrassment, in adhering to an exercise routine. Lower scores indicate greater endorsement. The Social Support and Exercise Survey (SSES; Sallis et al., 1987) was used to measure the degree to which participants received support from family members and friends for exercise endeavors. Participants' motivations for exercising in general and for completing the cybercycle study, specifically, were assessed. The Motives for Physical Activities Measure—Revised (MPAM-R; Ryan et al., 1997) was used to evaluate general exercise motivations. Participants rated the degree to which they were exercising for various reasons including wanting to be fit, look better, stay in shape, and because others motivating them.

Motivation to exercise for cognitive benefit

Given unexpected findings noted below, we probed our dataset for items that tapped participant motivation to exercise for cognitive benefit (MECB). Two items were identified that appeared to capture this construct. One item was taken from the Cybercycling Attitudes Test (CAT), which was developed by Nimon et al. (2009) to measure attitudes towards the cybercycle intervention: "*Exercising on the cybercycle will make me think more clearly*" (Likert scale 0–5, disagree to agree). The other item (#34) was taken from the EBBS: "*Exercising increases my mental alertness*" (Likert scale 1–4, agree to disagree). The EBBS item was reversed scored and scaled to match the CAT. These items were found to be somewhat correlated ($r = 0.33$) and summed to form a two-item measure of MECB.

Other measures

Participants were characterized as meeting criteria for mild cognitive impairment (MCI), if they scored −1.5 SD on three domains in the RCT's comprehensive neuropsychological battery (Jak et al., 2009). Participants' health was assessed using the Pennebaker Inventory of Limbic Languidness (the PILL) to assess participants' experience of common health symptoms (PILL; Pennebaker, 1982). The PILL assesses how often people have recently experienced various common symptoms and sensations, such as swollen joints, asthma, and dizziness.

STATISTICAL ANALYSES

Partial correlations were conducted in SPSS version 19 (IBM Corporation, 2012). Descriptive statistics were computed in EXCEL (Microsoft Corporation, 2010).

RESULTS

PRELIMINARY RESULTS

The current sample ($n = 30$) was compared with those who completed the original RCT but did not participate in the naturalistic window ($n = 33$). No significant differences were found on key variables (i.e., age, education, MCI status, EF) between the sample herein of those continuing to be followed in the study after the RCT and those from the original sample who did not continue on to participate in the naturalistic exercise window. Descriptive data is presented in **Table 1**.

PREDICTORS OF EXERCISE ADHERENCE

Partial correlations (list-wise) were conducted to examine the relationship between exercise frequency (number of rides on the cybercycle based on participants ride logs; average duration = 35.7 min and average intensity = 130 kcal) and change in EF (formula above adapted from Best et al., 2014), as well as exercise attitudes (benefits, barriers, social support, self-efficacy, and motivations), other possible predictors (MCI status, physical illness), all while controlling for randomized group assignment, age, education, and baseline EF.

Initial analyses including all eligible cases ($n = 30$) revealed a trend-level negative correlation between EF improvement (during prior RCT) and subsequent exercise frequency; indicating, that contrary to expectations, those with declining EF at the start of the naturalistic window went on to exercise more frequently than those who had made EF gains ($r = 0.38$; $p = 0.0549$). As noted above, consistent with Best et al. (2014) approach of excluding outliers, one extreme outlier was identified and removed from analyses. The reanalysis confirmed a strong inverse relationship between prior EF decline and later exercise adherence ($r = 0.43$; $p = 0.03$). Partial correlation results are reported in **Table 2**.

Because of the above noted unexpected inverse relationship between EF improvement and exercise adherence, we considered the possibility that our sample might differ from typical exercise studies in that the intervention was novel (combining interactive mental and physical exercise), and participants had received information regarding the possible cognitive benefits of exercise. Furthermore, since our sample was older than those in the study by Best et al. (2014) and many other typical exercise RCTs, we did have a greater proportion that was already starting to experience some cognitive decline and might be thus more motivated to try to improve their function and slow decline. We wanted to evaluate the possible impact of participants' motivation to exercise due to this unique feature of the RCT intervention and reviewed our data set for specific items that tapped participant motivation to exercise for possible cognitive benefits (see items identified and selected under Section Measures above). Motivation to exercise for cognitive benefit was thus also evaluated for its relationship to outcomes, and while statistically non-significant, indicates a possible trend ($r = 0.35$; $p = 0.08$).

A significant relationship between self-efficacy for physical activity and ride frequency ($r = 0.52$; $p = 0.01$) was also seen, in that individuals with higher exercise self-efficacy were found to exercise more frequently during the naturalistic window compared to those with lower personal efficacy for physical activity. This finding is in line with TPB and supports previous findings (Ajzen, 1985; McAuley and Blissmer, 2000; McAuley et al., 2011). Additionally, a significant inverse relationship was found between motivation to exercise for physical appearance and exercise adherence ($r = -0.41$, $p = 0.04$).

DISCUSSION

Results of a small sample of older adults exercising following a 3-month randomized trial of exergaming vs. traditional exercise, suggests a somewhat curious and unexpected relationship between EF and self-regulated engagement in exergaming. The relationship found herein suggests

Table 1 | Demographics of current sample compared with the non-continuing sample.

	Current sample[a]			Non-continuing sample[b]			
	ave	**SD**	***n***	**ave**	**SD**	***n***	***p***
Demographics							
group (% cybercycle group)	60%		30	36%		33	0.06
age	79.5	9.2	30	78.5	8.5	33	0.64
education (yrs)	14.1	3.2	30	13.6	1.9	33	0.45
sex (% female)	67%		30	79%		33	0.29
MCI classification	40%		30	21%		33	0.11
Exercise outcome							
ride frequency	21.0	20.2	30	27.8	25.8	23	0.29
Executive function							
Stroop C-A	29.24	14.6	30	29.71	23.7	31	0.93
Stroop C-A (prior intervention change: post-pre)[c]	−3.99	0.32	30	0.32	12.02	29	0.17
Exercise attitudes							
Exercise benefits and barriers scale (benefits)	61.9	7.2	30	59.7	13.6	26	0.43
Exercise benefits and barriers scale (barriers)	35.7	7.6	30	39.54	8.5	26	0.08
Social support for exercise scale (family)	22.8	12.6	30	23.1	10.2	25	0.93
Social support for exercise scale (friends)	24.6	11.3	30	23.9	11.1	22	0.83
Self-efficacy physical activity scale (total)	46.3	9.4	30	46.5	10.3	31	0.94
Motivation for physical activity measure (enjoy)	35.3	9.3	30	33.1	12.0	30	0.43
Motivation for physical activity measure (appearance)	29.4	7.7	30	27.8	9.8	30	0.48
Motivation for physical activity measure (fitness)	32.0	4.2	30	30.2	5.8	30	0.17
Motivation to exercise for cognitive benefit	9.0	1.4	30	8.1	2.9	32	0.14

Note: Data on measured variables were collected post-randomized exercise/pre-naturalistic exercise.

[a] *The "Current Sample" refers to those who completed the original RCT and the follow-up (even if they had zero rides).*

[b] *The "Non-continuing Sample" refers to those who completed the original RCT, but not the follow-up.*

[c] *Used change in difference score formula consistent with Best et al. (2014).*

an inverse relationship between EF improvement and the frequency of exergaming, which contradicts previous literature on the effects of EF on exercise adherence via increased self-regulation (McAuley et al., 2011; Best et al., 2014). Among this particular sample of older adults, decline in EF during a prior exercise intervention was associated with greater exercise frequency during a follow-up window.

One hypothesis to explain this apparent inverse relationship is that given the nature of this sample (older than some exercise trial samples) and the specific type of exercise involved (i.e., exergaming, involving interactive mental and physical exercise), the exergaming may have been more motivating for participants who were already experiencing some cognitive decline as they may have been hopeful it would yield cognitive benefit. This would fit with TST, as participants experiencing some cognitive decline might be more willing to engage immediate exercise given the possibility that they might yield cognitive and physical health benefits eventually. However, our examination of items related to MECB did not yield a statistically significant relationship, but a possible trend in the expected direction with the outcome of exercise behavior (cybercycle rides). It may be that our *post hoc* generated measure of motivation was not sufficient to capture this factor or that of other factors may be more important in determining the relationship between EF and exercise behavior. Physical appearance was the only motivation item that produced a significant relationship with exercise behavior, in that motivation to exercise for physical appearance was inversely related to exercise adherence. Withall et al. (2011) found a similar finding in their examination of individuals' motivations for engaging in an organized physical activity. One hypothesis for their finding is that those who indicated they were motivated to exercise for physical appearance may have dropped out if they did not see immediate improvements in their appearance. Additionally, previous studies which have found motivation to exercise for physical appearance to decrease with age (Trujillo et al., 2004; Dacey et al., 2008), suggesting that our population is likely more motivated by other factors. In keeping with TST, it may be that participants were more motivated to exercise due to intrinsic factors, rather than extrinsic reasons. Future research is needed to examine the specific relationship between EF, self-regulation, and exercise behaviors when exergaming is employed. It may be important to develop and measure motivation for exercise to benefit cognition, and to specifically focus on the relationship among these variables when targeting exercise interventions for older adults with some cognitive impairment.

Another possible explanation for the unexpected inverse relationship between EF and exercise behavior is that those who did not exercise on the cybercycle during the naturalistic exercise period may have engaged in other physical activities, such as walking on a treadmill. This was not prospectively assessed and is a limitation of this study; rather we depended on participants to sustain the expectation of "no changes to current physical activity" as stated at the beginning of the study. However, a few

Table 2 | Partial correlations with ride frequency.

	Ride frequency			
	Sample post-RCT[a] ($n = 30$)		Excluding outlier ($n = 29$)	
	r	*p*	*r*	*p*
Demographics				
MCI classification	0.18	*0.38*	0.13	*0.54*
Physical illness scale	0.08	*0.69*	0.06	*0.77*
Executive function				
Stroop C-A (prior intervention change: post-pre)[b]	0.38	***0.05***	0.43	***0.03***
Exercise attitudes				
Exercise benefits and barriers scale (benefits)	−0.28	*0.16*	−0.15	*0.47*
Exercise benefits and barriers scale (barriers)	0.37	*0.06*	0.37	*0.07*
Social support for exercise scale (family)	−0.10	*0.62*	−0.11	*0.59*
Social support for exercise scale (friends)	0.03	*0.89*	−0.05	*0.81*
Self-efficacy physical activity scale (total)	0.52	***0.01***	0.42	***0.04***
Motivation for physical activity measure (enjoy)	−0.15	*0.48*	−0.20	*0.33*
Motivation for physical activity measure (appearance)	−0.41	***0.04***	−0.55	***0.004***
Motivation for physical activity measure (fitness)	0.00	*1.00*	0.01	*0.98*
Motivation to exercise for cognitive benefit	0.35	*0.08*	0.32	*0.12*

Note. Control variables included: group, age, education, and prior executive function (at enrollment).

[a] The "Sample post-RCT" refers to those who completed the original RCT and the follow-up (even if they had zero rides).

[b] Used change in difference score formula consistent with Best et al. (2014).

participants noted in the bike logs that they had participated in other physical activity (e.g., treadmill time). Future research should prospectively and specifically track other physical activity.

Another consideration in interpreting these findings is that family members and caregivers of older adults experiencing some cognitive decline may serve as external motivators, changing self-regulation into other-regulation. For example, a spouse may be concerned that their loved one is not as mentally sharp and fears further decline into dementia, so they may increase their own efforts to facilitate a participant showing up for their allotted exercise slot on the cybercycle. Although we did assess social support for exercise, it is unclear whether some participants would have been able to report this in a way that would capture the possibly subtle, but substantial impact of instrumental assistance some caregivers may have been providing. Future research might find a way to clarify this possible impact on regulation by extension.

Furthermore, it is possible that these results do not entirely contradict the recent report of Best et al. (2014), but rather may illuminate a more complex relationship between changing cognition across later life and exercise behaviors. The sample in their study was comprised of women nearly 70 years old with normative performance on a screen for MCI, whereas our sample was on average a decade older and more impaired overall (40% met criteria for MCI). Thus, some in our sample would have been slipping cognitively regardless of intervention, and while exercise may not have "improved" EF in an absolute way for some, it may have slowed decline (e.g., Lautenshlager et al., 2008). Our sample may have overlapped with Best's sample, including some normative participants for whom a positive linear relationship with exercise adherence could apply; however, result may be clouded by the mix of more impaired participants for whom may exist a different relationship between EF and adherence. A larger sample, perhaps also a matching sample of normative and MCI participants, would be needed to discern the possible merits or lack thereof of this speculation.

STRENGTHS

These participants engaged previously in two randomized exercise conditions that provided an interesting comparison since they both involved the same aerobic exercise, but varied mental interactivity. Other studies may assign participants to groups that involve different forms of exercise that may not be comparable on a key variable such as HR (Best et al., 2014), while others may compare an older adult group that is engaging in exercise and a group that is engaging in a non-physical activity (Evers et al., 2011). Participants in the present research engaged in the same type of physical activity during the RCT, thus providing an equivalent starting point in terms of recent prior physical activity; that is, no group was inadvertently advantaged/disadvantaged by having to "catch up" on aerobic exercise, which could have affected results. Instead, during the naturalistic exercise window studied herein, all participants were free to immerse themselves in a virtual tour while engaging aerobic exercise to which their body would have already become accustomed.

Unlike some previous research, there was no transportation barrier for these participants. The equipment and all necessary materials were available in the participant's residences for ease of access. This greatly reduced the amount of effort required of participants which has been found to deter exercising in previous studies, such as bad weather or having to take public transportation (Evers et al., 2011).

LIMITATIONS

A major limitation of this study was the impact of randomized experience in the control (bike only) and experimental group (cybercycle). By giving the participants the freedom to choose which way they would like to use the bike after the initial 3-month intervention period, those participants that were on the stationary bike seem to have engaged in the cybercycle more frequently, perhaps in part due to its novelty. Those who had been originally assigned to the cybercycle may have lost interest after having been required to exercise on it for 3 months, thus either discontinuing or perhaps choosing different (unspecified/non-bike) forms of exercise. As noted above, this limitation should be addressed in future research by prospective assessment of other forms of physical activity. Other limitations include the small sample size and the variability of the sample (some clearly normative older adults, with some starting to experience cognitive decline). The use of multiple statistical tests also may have led to escalating Type I error rates.

FUTURE RESEARCH

Future research might be able to further explore these preliminary findings by examining a larger sample of older adults with some cognitive decline present, and carefully measuring EF, self- and other-regulation, exercise behaviors (as targeted, but also with consideration of non-compliance), and if examining a novel form of exercise, such as exergaming, consider measuring specific variables that could be salient (such as MECB). A larger sample would allow more sophisticated analysis of mediation and moderator models, as well as consideration of change over time that was precluded here by a small sample.

CONCLUSION

This report presents preliminary evidence of an unexpected inverse relationship between EF and exercise adherence among older adults. It was hypothesized that that this relationship might be explained by some cognitive decline present in the sample and increased motivation to exercise to protect cognitive function. The latter being an outcome perceived to be possible via the unique interactive mental and physical exercise offered in the exergame (virtual reality stationary bike) utilized herein. Further research is warranted with a larger sample, enabling comparison of possible subgroups (e.g., normative vs. MCI), and examining additional factors affecting motivation and adherence (e.g., exercising for cognitive benefit and/or the possible instrumental role of caregivers in adherence).

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The effects of acute aerobic activity on cognition and cross-domain transfer to eating behavior

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Prior studies have demonstrated that a single session of aerobic exercise can enhance cognitive functioning; specifically, the inhibition facet of executive function (EF). Additionally, previous research has demonstrated that inhibitory abilities are essential for effective dietary self-control. However, it is currently unknown whether exercise induced enhancements in EF also facilitate self-control in the dietary domain. The present study sought to determine whether a single session of aerobic exercise enhances EF, and whether there is a transfer effect to dietary self-control. Thirty four undergraduate students were randomly assigned to one of three exercise conditions: (1) minimal exercise; (2) moderate intensity exercise (30% heart rate reserve); (3) vigorous intensity exercise (50% heart rate reserve). After the exercise bout, participants completed three standardized EF tasks followed by a bogus taste test for three appetitive snack foods (milk chocolate and potato chips) and two control foods (dark chocolate and crackers). The amount of food consumed during the taste test was covertly measured. The results revealed a significant main effect of treatment condition on the Stroop task performance, but not Go-NoGo (GNG) and Stop Signal task performance. Findings with respect to food consumption revealed that EF moderated the treatment effect, such that those with larger exercise effects on Stroop performance in the moderate intensity exercise condition consumed more control foods (but not less appetitive foods). These findings support the contention that a single bout of aerobic exercise enhances EF, and may have transfer effects to the dietary domain, but that such effects may be indirect in nature.

Keywords: aerobic exercise, acute exercise, executive function, snack foods, food intake

INTRODUCTION

There has been recent interest in the beneficial effects of acute bouts of aerobic exercise on cognition. A recent meta-analysis suggested that acute bouts of aerobic activity are associated with a small but reliable positive effect on cognitive performance ($ES = 0.20$; Lambourne and Tomporowski, 2010). Moderators of the effect size include temporal sequencing of cognitive assessment in relation to exercise (following bout>during bout), modality of aerobic training (cycling>running), and task type (memory>processing speed; Lambourne and Tomporowski, 2010). With respect to executive function (EF) in particular, results have been variable with some studies showing moderate-to-large effects (Chang and Etnier, 2009; Pontifex et al., 2009; Chang et al., 2011), and others showing no beneficial effect (Tomporowski and Ganio, 2006; Coles and Tomporowski, 2008). These inconsistencies may be related to study design, exercise type, or facet of EF examined. To date, the majority of studies examining the effects of acute aerobic exercise on EF have focused on the inhibition facet of EF using the Stroop task (Hogervorst et al., 1996; Sibley et al., 2006; Barella et al., 2010; Lambourne and Tomporowski, 2010; Yanagisawa et al., 2010). Of these, Stroop task performance tended to improve following exercise in both young (Hogervorst et al., 1996; Sibley et al., 2006; Yanagisawa et al., 2010) and older adults (Barella et al., 2010). Furthermore, Yanagisawa et al. (2010) demonstrated that acute aerobic exercise increased cortical activation of the left dorsolateral prefrontal cortex (DLPFC) during the Stroop task, and this enhanced activation corresponded with improved performance on the Stroop task. Taken together, these studies suggest that acute aerobic exercise especially enhances the inhibitory control facet of EF.

Nonetheless, it remains unclear what, if any, implications exercise-induced enhancements in inhibitory control might have on everyday activities that rely on such abilities. Recent studies have suggested that inhibitory abilities may play an important role in self-regulatory processes required for dietary self-restraint (Rotenberg et al., 2005; Guerrieri et al., 2009, 2012; Nederkoorn et al., 2009; Houben and Jansen, 2011; Hall, 2012; Hall et al., 2013). If enhancements in EF—and inhibition specifically—are induced by acute aerobic activity, it is possible that such enhancements may facilitate self-control in the dietary domain as well, either directly or indirectly. Exercise induced enhancements in EF may directly facilitate dietary self-control by moderating the quantity of food consumed. However, it is also plausible that such enhancements may indirectly facilitate dietary self-control, by moderating the type of food consumed (i.e., healthy vs. unhealthy foods). The current study was designed to test these possibilities. It was hypothesized that aerobic activity would enhance EF, particularly when measured with the Stroop task, and that improvements in Stroop performance would predict reduced consumption of appetitive (unhealthy) foods in a subsequent laboratory taste test paradigm. We also examined the possibility of indirect transfer to consumption of control (perceived healthier) foods.

METHODS

PARTICIPANTS

Thirty-four undergraduate students, aged 18–27 (*M* = 20.24; *SD* = 1.76), were recruited from psychology courses; sample characteristics are presented in **Table 1**. Participants received course credits in exchange for their participation. All participants indicated that they were inactive (i.e., sedentary), and liked the experimental foods (milk chocolate and potato chips) in a pre-screening questionnaire; the screening procedure is outlined below. Written and informed consent was obtained from all participants. This study was reviewed by and received approval from the University of Waterloo Research Ethics Board, and was conducted in accordance with standard ethical protocols.

PRE-SCREEN MEASURES

Several weeks prior to study participation, potential participants completed a pre-screening package, which included items to identify sedentary individuals that also liked the experimental foods. Self-reported exercise was measured using the Bogg Exercise Scale (Bogg et al., 2008). Participants that exercised less than two times per week, according to this scale, were deemed inactive and eligible to participate in the study. In addition, the following two items (adapted from Hill et al., 1991) were used to identify participants who liked potato chips and chocolate: (1) "how often do you experience cravings to eat potato chips/chocolate?" (response scale: 1 = "never"; 10 = "all the time"); (2) "how strong are these cravings you experience to eat potato chips/chocolate" (response scale: 1 = "extremely weak"; 10 = "extremely strong"); individuals who scored 7 or above on the response scale for both items and both experimental foods were deemed eligible to participate in the study.

PROCEDURE

Eligible participants were tested individually in a single laboratory session lasting approximately 2 h. All participants were required to abstain from eating or drinking any caffeinated beverages 3 h prior to their scheduled session, with compliance checked upon their arrival. All laboratory sessions were conducted at the same time of day (3:30–5:30 PM). At the start of each exercise session, participants completed the Physical Activity Readiness Questionnaire (PAR-Q). The PAR-Q is a seven item questionnaire designed to screen for any health conditions that could be exacerbated by exercise; no participants were excluded due to health conditions.

For the aerobic exercise bout, participants were randomly assigned to one of three exercise conditions: (1) minimal exercise; (2) moderate intensity exercise (30% heart rate reserve); (3) vigorous intensity exercise (50% heart rate reserve). Exercise bouts were conducted using a recumbent cycle ergometer. Participants were fitted with a heart rate monitor prior to exercise, and heart rate was monitored continuously and recorded every 5 min. Resting heart rate was measured after participants rested for 1 min the cycle ergometer prior to exercise.

For the minimal exercise condition, participants cycled at a slow and steady rate, 30–40 rpm, without significantly increasing their heart rate. The exercise session lasted a total of 35 min, and consisted of a 5 min warm-up, 25 min of exercise at target heart rate (THR) (the first 5 min were used to bring heart rate up to the THR), and a 5-min cool-down.

For the moderate exercise condition, participants began pedaling at 60–70 rpm. Work load was then increased in 10 W increments to gradually raise heart rate from resting to the THR. THR was established based on heart rate reserve (HRR). Heart rate reserve was calculated as maximal heart rate (MHR), estimated using the formula 220-age, minus resting heart rate (RHR). Next, THR was calculated by multiplying HHR by the target intensity, 30% for the moderate condition and 50% for vigorous condition, and adding it to RHR (THR = RHR + (MHR − RHR) TI%). Exercise duration was the same as that for minimal condition. The vigorous condition was identical to the moderate condition except that intensity was established at 50% HRR.

Immediately following the exercise bout, participants completed three computer-administered EF tasks; the order of the tasks was counterbalanced across participants. The total duration of all three EF tasks was approximately 30 min. Directly following the EF tasks, participants were asked to report their current subjective level of hunger (on a 1–10 scale), and subsequently completed a bogus taste test. Prior to each experimental session, the weight of the experimental foods were measured and recorded. For the taste test, participants were instructed to taste and rate the subjective properties (i.e., texture, sweetness, and saltiness) of each experimental food. Participants received instructions to consume as much food as they would like, and to tell the experimenter when they had completed their ratings. During the taste test, the experimenter left the room until the participant indicated they had completed the taste test, at which point the next food was presented; the time each participant took to complete their taste ratings was covertly measured. On average, the total duration of the taste was 13 min (*SD* = 5.58). The experimental foods were presented in the following order: (1) Belgian milk chocolate; (2) Belgian dark chocolate; (3) regular potato chips; (4) flavored potato chips; (5) soda crackers. Participants were not provided with any information regarding the macronutrient content of the experimental foods. Following the taste test, the experimental foods were weighed and the amount of food consumed (grams) during the taste test was recorded.

FOOD CONSUMPTION MEASURES

The taste test foods were divided into two categories: (1) appetitive foods (milk chocolate and potato chips); (2) control foods (dark chocolate and crackers). The following item from the taste rating questionnaire was used to confirm that participants perceived the appetitive foods as more appealing than the control? foods "Overall, how would you rate this food?" (response scale: 1 = "not at all good"; 10 = "very good"). As expected, participants rated the appetitive foods as significantly more appealing than the control foods [$t_{(33)} = 9.266, p < 0.001$].

Table 1 | Participant demographic, EF task performance, and food consumption by exercise condition.

	Minimal (*n* = 12)		**Moderate (*n* = 10)**		**Vigorous (*n* = 12)**	
	Mean (*SD*)	**% (*n*)**	**Mean (*SD*)**	**% (*n*)**	**Mean (*SD*)**	**% (*n*)**
Age (years)	19.5 (2.53)		19.5 (1.08)		20.17 (0.94)	
BMI	22.8 (3.7)		22.03 (2.64)		22.25 (3.36)	
Hunger	6.8 (2.61)		5.4 (1.51)		6.08 (1.8)	
GENDER						
Male		41.7 (5)		40.0 (4)		16.7 (2)
Female		58.3 (7)		60.0 (6)		83.3 (10)
ETHNICITY						
Caucasian/white		50.0 (6)		20.0 (2)		33.3 (4)
Asian		41.7 (5)		40.0 (4)		50.0 (6)
Black						8.3 (1)
Hispanic				10.0 (1)		
South Asian		8.3 (1)		10.0 (1)		8.3 (1)
Middle Eastern				20.0 (2)		
EXECUTIVE FUNCTION MEASURES						
GNG RT (ms)	404.05 (33.73)		392.91 (26.44)		410.43 (28.69)	
SST accuracy (% incorrect on stop trials)	0.19 (0.16)		0.17 (0.13)		0.20 (0.17)	
Stroop interference (ms)	315.51 (328.13)		−110.7 (336.67)		60.61 (293.36)	
FOOD CONSUMPTION MEASURES						
Total food consumed (grams)	75.36 (23.37)		89.0 (30.88)		78.42 (28.05)	
Total appetitive foods consumed (grams)	59.36 (22.74)		69.2 (25.6)		59.75 (20.36)	
Total Control Food Consumed (grams)	16.0 (5.67)		19.8 (8.8)		18.67 (12.04)	

EXECUTIVE FUNCTION MEASURES

All EF measures were presented via E-Prime software (Psychology Software Tools, Inc) on a desktop computer; participant responses were made via button press using a response box. Participants were instructed to respond as quickly and accurately as possible for all tasks.

STROOP TASK

The Stroop task (Stroop, 1992) was modeled after the variant in Miyake et al. (2000). The Stroop task is a reliable EF measure (Strauss et al., 2005; Friedman et al., 2008), and is one of the most widely used measures of response inhibition. In this particular version of the task, participants were instructed to name the color of stimulus presented on a computer screen. All stimuli were presented individually in one of six colors: blue, green, orange, purple, red, or yellow. The task consisted of a mixed block of trials containing 72 trials with a string of asterisks, 60 incongruent color word trials (e.g., the word blue appearing in red colored font) and 12 congruent color word trials (e.g., the word blue appearing in blue colored font). For each trial, the stimuli were presented on the screen until the participant responded, followed by a response to stimulus interval of 1000 ms minus the response time. The crucial dependent variable was the Stroop inference effect, calculated as the reaction time on correct incongruent trials minus the reaction time on correct congruent trials; shorter reaction times were taken to reflect stronger EFs.

GO/NO-GO TASK

The Go-NoGo (GNG) task is a widely used and reliable measure of response inhibition (Kuntsi et al., 2005). In this variant of the GNG task, participants were instructed to press a button as quickly as possible whenever a lower case letter was presented on the computer screen, and withhold their response whenever an upper case letter appeared on the computer screen. For each trial, the stimulus duration was set at 1000 ms, with a 500 ms interstimulus interval. The task consisted of eight blocks, with 60 trials in each block. In half of the test blocks upper case letters were predominant (5:1 ratio) and in the other half of the test blocks lower case letters were predominant (5:1 ratio). The crucial dependent variable was reaction times on correct trials; shorter reaction times were taken to be indicative of stronger EFs.

STOP SIGNAL TASK

The Stop Signal Task (SST; Logan et al., 1984) was modeled after the variant in Miyake et al. (2000). Like the other EF tasks, the SST is a reliable measure of inhibition (Friedman et al., 2008; Congdon et al., 2012). In this particular version of the SST task, participants completed two blocks of trials. The first block of 48 trials was used to build up a prepotent categorization response. Participants were instructed to categorize a series of words, presented individually on a computer screen, as an animal or non-animal word. During the second block of 96 trials (stop trials), participants completed the same categorization task, but they were instructed to not respond (i.e., withhold their response) when they heard a computer emitted tone (stop signal; 23 trials). The stimulus duration was 1500 ms with a 500 ms interstimulus interval. The stop signal delay (the duration between the onset of trial and the time at which the stop signal occurred) was adjusted for each participant by subtracting 225 ms from the mean reaction time on go trials. The crucial dependent variable was the proportion of incorrect responses on stop trials (i.e., responding when the stop signal was present); higher accuracy on the stop trials was taken to signify stronger EFs.

STATISTICAL ANALYTIC PROCEDURE

The accuracy for the both the Stroop ($M = 0.94$; $SD = 0.11$) and the GNG ($M = 0.89$; $SD = 0.14$) tasks were uniformly high, and so analyses focussed on accuracy-corrected reaction times in both cases. To reduce the potential influence of outliers, a Winsorizing technique was applied to outlier reaction times for the Stroop and GNG task; outlier scores were removed and replaced with the next sequential value. Next, to confirm group randomization, a one-way Analysis of Variance (ANOVA) was conducted to compare age, sex, current hunger, and BMI across experimental conditions.

To test the hypothesis that a single session of aerobic exercise would enhance EFs, a one-way ANOVA was conducted to compare performance on the Stroop, GNG, and SST across exercise conditions. Significant main effects were followed up with planned Fisher's LSD comparisons. Following this, a one-way ANOVA was conducted to determine if there was a significant treatment effect on the total amount of food consumed, the total amount of appetitive food consumed, and the total amount of control food consumed. Next, hierarchical moderated multiple regression analyses were conducted to determine if there was a moderating effect of EF on food consumption across treatment conditions. Following the procedures outlined in Aiken and West (1991), effect coding was used to denote group membership; the experimental conditions (i.e., exercise condition) were coded into two vectors (i.e., +1, 0, −1). The main effect variables (exercise condition and EF scores) were centered and combined into an interaction term. The main effects were entered on the first step of the hierarchical linear regression analysis, followed by the interaction terms on the second step. Separate regression analyses were conducted for each EF task to determine if (1) there is a moderating effect of EF on the total amount food consumed, and (2) if there is a moderating effect of EF on the differential consumption of appetitive (milk chocolate and potato chips) and control (dark chocolate and crackers) foods. All statistical analyses were conducted using SPSS software (version 21; IBM Corp, 2012). All statistical analyses were determined a priori.

RESULTS

The three experimental groups did not differ significantly with respect to age [$F_{(2,\ 31)} = 1.878, p = 0.170$], sex [$F_{(2,\ 31)} = 1.016, p = 0.374$], BMI [$F_{(2,\ 31)} = 0.18, 2, p = 0.835$] and subjective hunger ratings [$F_{(2,\ 31)} = 0.39, p = 0.683$], indicating that randomization was successful. Zero order correlation for study variables are presented in **Table 2**. Across all participants, none of the variables were significantly correlated with the total amount of food, the total amount of appetitive food, and the total amount of control food consumed; however, GNG reaction time was marginally significantly correlated with the total amount of food consumed ($p = 0.06$) and the total amount of control food consumed ($p = 0.07$). Stronger GNG and SST performance predicted significantly lower subjective hunger ratings. Food variables were significantly correlated with one another.

EFFECTS OF EXERCISE ON EF

A significant main effect of treatment condition on Stroop task performance [$F_{(2,\ 31)} = 5.017$, $p = 0.013$, $d = -1.044$] was observed. Compared to the minimal exercise condition, performance on the Stroop task was significantly better in the moderate intensity exercise condition ($p = 0.004$), and marginally better in the vigorous intensity exercise condition ($p = 0.059$; see **Figure 1**). No significant effects of treatment condition on GNG [$F_{(2,\ 31)} = 0.942, p = 0.401, d = -0.053$] or SST [$F_{(2,\ 31)} = 0.122$, $p = 0.885$, $d = 0.011$] performance were observed. The mean reaction times for GNG and Stroop, and the mean accuracy for SST by exercise condition are shown in **Table 1**.

EFFECTS OF EXERCISE ON FOOD CONSUMPTION

There was no significant effect of experimental condition on the total amount of food consumed [$F_{(2,\ 31)} = 0.703, p = 0.503, d = 0.282$], the total amount of appetitive food consumed [$F_{(2,\ 31)} = 0.622, p = 0.544, d = 0.204$], or the total amount of control food consumed [$F_{(2,\ 31)} = 0.466, p = 0.632, d = 0.332$). That is, exercise did not differentially induce consumption differences across conditions for any food type or total food.

INTERACTION BETWEEN EXERCISE AND EF ON SNACK FOOD CONSUMPTION

When total amount of food consumed was entered as the dependent variable, hierarchical moderated regression analyses indicated that there was no significant interaction between Stroop performance and the treatment effect for the vigorous ($\beta = 0.173$, $t = 0.737$, $p = 0.467$, $d = 0.359$) and moderate ($\beta = -0.176$, $t = -0.747$, $p = 0.461$, $d = 0.368$) intensity exercise group. Similar results were observed among the other two EF tasks: no significant interaction was observed between GNG performance and the treatment effect for the vigorous ($\beta = -0.194$, $t = -0.898$, $p = 0.377$, $d = -0.404$) and moderate ($\beta = -0.070$, $t = -0.315$, $p = 0.755$, $d = -0.144$) intensity exercise groups, and SST performance and the treatment effect for the vigorous ($\beta = -0.086$, $t = 0.304$, $p = 0.763$, $d = -0.176$) and moderate ($\beta = 0.129$, $t = 0.395$, $p = 0.696$, $d = 0.268$) intensity exercise groups. Comparable results were observed when examining the total amount of appetitive foods consumed. No interaction was observed between performance on the Stroop task and the treatment effect for the vigorous ($\beta = 0.007$, $t = 0.030$, $p = 0.976$, $d = 0.014$) and moderate ($\beta = -0.007$, $t = 0.110$, $p = 0.913$, $d = -0.014$) intensity exercise groups. Additionally, there was no interaction observed between GNG performance and the treatment effect for the vigorous ($\beta = -0.078$, $t = -0.352$, $p = 0.728$, $d = -0.160$) and moderate ($\beta = -0.128$, $t = -0.561$, $p = 0.579$, $d = -0.265$) intensity exercise groups, and SST performance and the treatment effect for the vigorous ($\beta = 0.159$, $t = 0.564$, $p = 0.578$, $d = 0.329$) and moderate ($\beta = -0.032$, $t = 0.097$, $p = 0.924$, $d = -0.066$) intensity exercise groups.

When examining the total amount of control foods consumed, a significant interaction between Stroop performance and the treatment effect was observed for the vigorous ($\beta = 0.497$, $t = 2.285$, $p = 0.030$, $d = 1.179$) and the moderate ($\beta = -0.459$, $t = -2.100$, $p = 0.045$, $d = -1.069$) intensity

Table 2 | Correlations between measures.

	1	2	3	4	5	6	7	8	9	10
1. Age	1									
2. Sex	−0.06	1								
3. BMI	0.19	−0.10	1							
4. Hunger	0.34*	0.17	0.18	1						
5. SST Accuracy	0.20	−0.01	0.38*	−0.35*	1					
6. GNG RT	0.36*	0.28	−0.08	0.29*	0.17	1				
7. Stroop interference	0.10	0.23	0.08	−0.16	0.01	−0.005	1			
8. Total food consumed	0.06	−0.19	0.06	0.12	0.05	−0.27†	−0.21	1		
9. Total appetitive food consumed	−0.03	−0.20	−0.04	0.13	0.02	−0.22	−0.20	0.95**	1	
10. Total control food consumed	0.26	−0.13	0.28	0.02	0.05	−0.26†	−0.13	0.64*	0.36*	1

*Spearman's rho was used to calculate sex based correlations. †Correlation is significant at the $p < 0.10$ level (1-tailed); *correlation is significant at the $p < 0.05$ level (1-tailed); **correlation is significant at the $p < 0.01$ level (1-tailed).*

groups. Specifically, those in the moderate intensity condition showed a marginally significant positive association between Stroop performance and the amount of control food consumed ($\beta = -0.617$, $t = -2.216$, $p = 0.058$). There was no significant variability in the amount control food consumed in the vigorous ($\beta = 0.380$, $t = 1.298$, $p = 0.224$) and minimal ($\beta = -0.158$, $t = -0.482$, $p = 0.642$) intensity groups. A marginally significant interaction between GNG performance and the treatment effect was observed for the vigorous intensity exercise condition ($\beta = -0.385$, $t = -1.819$, $p = 0.080$, $d = -0.856$), such that those in the vigorous intensity exercise condition showed a marginally significant positive association between the amount of control food consumed and GNG performance ($\beta = -0.513$, $t = -1.890$, $p = 0.088$). There was no significant variability in the amount of control food consumed in the moderate intensity ($\beta = -0.125$, $t = -0.355$, $p = 0.732$) and minimal intensity ($\beta = 0.145$, $t = 0.440$, $p = 0.670$) groups. Furthermore, there was no significant interaction between SST performance and the treatment effect for the vigorous ($\beta = -0.137$, $t = -0.486$, $p = 0.63$, $d = -0.283$) and moderate ($\beta = 0.305$, $t = 0.929$, $p = 0.361$, $d = 0.660$) intensity exercise groups.

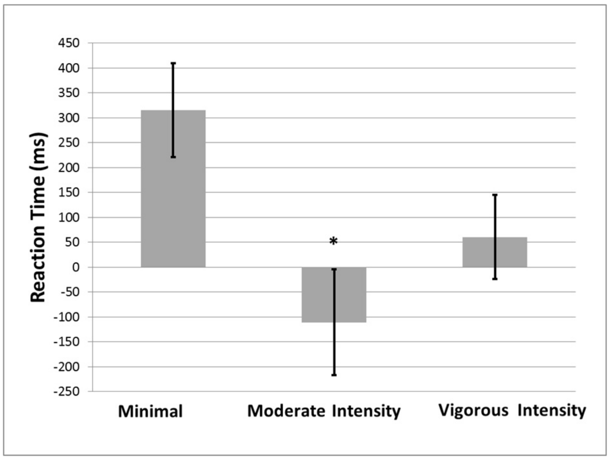

FIGURE 1 | Mean (±SE) Stroop interference effect (incongruent RT-congruent RT) as a function of exercise condition. *Significantly different from the minimal exercise condition at the $p < 0.05$ level (2-tailed).

DISCUSSION

In the current study, we examined the effects of an acute bout of aerobic activity (moderate and vigorous) on cognitive function, and assessed transfer effects to a self-control task in the dietary domain. An acute bout of moderate aerobic activity significantly improved performance on the Stroop task. However, there were no significant improvements in Stroop task performance following vigorous aerobic exercise, or in GNG and SST performance for either intensity. The current findings of a significant effect of moderate aerobic exercise on Stroop performance is consistent with the findings of several prior studies (Hogervorst et al., 1996; Sibley et al., 2006; Barella et al., 2010; Yanagisawa et al., 2010). The null findings in relation to GNG and Stop signal suggest that the effects of aerobic activity are not uniform across all measures of EF, or even across all measures of the inhibition facet of EF. However, it is also possible that subtle aspects of the requirements unique to each of the specific tasks were differentially sensitive to exercise. Additionally, reliability differences between the tasks could also have affected results; it is possible that the null effects observed would be significant with a more well-powered experimental design (either within subjects or between subjects with a larger sample size).

With respect to food consumption, there was no significant difference in energy intake following an acute bout of moderate or vigorous aerobic exercise, a finding that is consistent with the results of several other studies (King et al., 1994, 1997a,b; George and Morganstein, 2003; Deighton et al., 2012). Contrary to the hypothesized result, there was no moderating effect of EF on consumption of appetitive foods. There was, however, a moderating effect of EF on consumption of control foods. Specifically, those with larger exercise effects on Stroop performance in the moderate exercise condition consumed more control foods compared to those in the vigorous and minimal exercise conditions. These results may be attributed to differences in the perceived healthiness of the control and appetitive foods. An accumulating body of evidence suggests that the consumption of dark chocolate, as opposed to milk chocolate, may reduce the risk of developing cardiovascular disease (Taubert et al., 2003; Engler and Engler, 2006; Erdman et al., 2008; Ried et al., 2010; Di Renzo et al., 2013), and therefore it is possible that the control foods were perceived as healthier than the appetitive foods. Consequently, given that participants reported being moderately hungry prior to the start of the taste test, it is plausible that those with larger exercise effects on EF consumed more control foods as a means of energy compensation while still exerting self-control (i.e., consuming more of the perceived healthier foods). This contention is further supported by the taste rating effects. Across exercise conditions, participants rated the control foods as significantly less appealing than the appetitive foods, indicating that the experimental effect on control food consumption cannot be attributed to changes in taste preferences or perceptions.

These results provide evidence of a transfer effect to dietary self-control, but only in terms of indirect compensatory behaviors (i.e., those consumptive behaviors that may satisfy hunger by choosing to consume foods that are perceived as the healthiest alternatives available at the choice point). Direct transfer effects—wherein less appetitive foods are consumed—were not found. While the latter findings are initially counter-intuitive, together these findings suggest that exercise induced enhancements in EF may result in increased choice-related dietary self-control, which in turn moderated the type of food consumed rather than the quantity of food consumed. This explanation aligns well with prior research that has implicated the operation of the DLPFC in dietary self-control. For instance, Hare et al. (2009) reported that in comparison to those with weak self-control, individuals with effective self-control more often made decisions about which foods they would like to eat on the basis of perceived health (e.g., apple) rather than taste (e.g., chocolate bar). Additionally, regardless of individual differences in self-control strength, activity in the ventromedial prefrontal cortex (vmPFC) increased when participants made decisions about which foods to eat, however, increased DLPFC activity was observed only in those participants with effective self-control. Therefore, given that acute bouts of aerobic exercise have been shown to increase blood flow to the PFC, specifically the DLPFC (Yanagisawa et al., 2010), it is possible that choice-related self-control was enhanced following moderate aerobic activity. As a result, those with the largest exercise effects on EF may have chosen to consume foods on the basis of perceived health rather than taste, which explains the moderating effect of EF on the consumption of control foods (i.e., perceived healthier food).

Strengths of this study include the use of several measures of inhibition, and the assessment of a cross-domain transfer to dietary self-control, which has not been previously assessed. Additionally, the use of several different exercise intensity conditions provided a comprehensive assessment of the effects of acute aerobic activity on cognition, and of the cross-domain transfer to dietary self-control. The main limitation of this study was the small sample size, which may have reduced our power to detect some effects. Likewise, the use of an undergraduate sample may have reduced variability in our EF measures and therefore further limited our ability to detect effects. Nonetheless, there is currently a lack of prior research in this area, and therefore the results from this study provide some important preliminary findings.

In summary, our findings provide some support for the contention that a single bout of aerobic activity enhances cognitive function, though the effects were of considerable specificity in terms of measures used, and exercise bout intensity. Some evidence of transfer effects to dietary self-control were also observed, but these were specific to indirect effects (i.e., choice of foods perceived as relatively healthier rather than those perceived as relatively unhealthy). Future research should consider examining the effects of a single bout of aerobic exercise on different facets of EF (e.g., working memory, mental flexibility), to determine if aerobic exercise enhances all facets of cognitive functioning or just inhibition specifically. As well, the inclusion of objectively healthy food options (e.g., fruits and/or vegetables), in addition to the control and appetitive food options, in future studies would help to further elucidate this indirect transfer effect.

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Non-conscious visual cues related to affect and action alter perception of effort and endurance performance

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The psychobiological model of endurance performance proposes that endurance performance is determined by a decision-making process based on perception of effort and potential motivation. Recent research has reported that effort-based decision-making during cognitive tasks can be altered by non-conscious visual cues relating to affect and action. The effects of these non-conscious visual cues on effort and performance during physical tasks are however unknown. We report two experiments investigating the effects of subliminal priming with visual cues related to affect and action on perception of effort and endurance performance. In Experiment 1 thirteen individuals were subliminally primed with happy or sad faces as they cycled to exhaustion in a counterbalanced and randomized crossover design. A paired *t*-test (happy vs. sad faces) revealed that individuals cycled significantly longer (178 s, $p = 0.04$) when subliminally primed with happy faces. A 2 × 5 (condition × iso-time) ANOVA also revealed a significant main effect of condition on rating of perceived exertion (RPE) during the time to exhaustion (TTE) test with lower RPE when subjects were subliminally primed with happy faces ($p = 0.04$). In Experiment 2, a single-subject randomization tests design found that subliminal priming with action words facilitated a significantly longer TTE (399 s, $p = 0.04$) in comparison to inaction words. Like Experiment 1, this greater TTE was accompanied by a significantly lower RPE ($p = 0.03$). These experiments are the first to show that subliminal visual cues relating to affect and action can alter perception of effort and endurance performance. Non-conscious visual cues may therefore influence the effort-based decision-making process that is proposed to determine endurance performance. Accordingly, the findings raise notable implications for individuals who may encounter such visual cues during endurance competitions, training, or health related exercise.

Keywords: perception of effort, psychobiological model, endurance performance, subliminal, affect, action and inaction

GENERAL INTRODUCTION

The psychobiological model of endurance performance (Marcora, 2008; Marcora and Staiano, 2010), based on motivational intensity theory (Brehm and Self, 1989; Wright, 2008), proposes that the point at which people stop endurance exercise (i.e., exhaustion) is determined by perception of effort and potential motivation. Perception of effort is the conscious sensation of how hard, heavy and strenuous a physical task is (Marcora, 2010) whilst potential motivation is the highest effort a person is willing to exert in order to succeed in a task (Brehm and Self, 1989). Hence, when the effort required by endurance exercise is perceived to exceed potential motivation, or when perception of effort is so extreme that continuing the task seems impossible, the person consciously decides to stop exercising.

According to this effort-based decision-making model, any factor that influences perception of effort and/or potential motivation influences endurance performance, even when the physiological capacity to perform endurance exercise is unchanged. This proposal is in contrast to the muscle fatigue model of endurance performance in which exhaustion is thought to be caused by central and/or peripheral muscle fatigue (Allen et al., 2008; Amann and Dempsey, 2008; MacIntosh and Shahi, 2011) as well as the central governor model which proposes that the subconscious regulation of neural recruitment of locomotor muscles exists to avoid conscious override that may damage the human (Noakes, 2000; St Clair-Gibson and Noakes, 2004). Experimental evidence that conscious psychological manipulations like motivational self-talk (Blanchfield et al., 2014), placebo (Beedie et al., 2006), and competition (Wilmore, 1968) can increase time to exhaustion (TTE) supports the psychobiological model of endurance performance and provides strong evidence against both the muscle fatigue model of endurance performance (Allen et al., 2008; Amann and Dempsey, 2008; MacIntosh and Shahi, 2011) and the existence of a central governor that subconsciously regulates neural recruitment of locomotor muscles based on afferent feedback about the physiological condition of the body (interoception) (Craig, 2002) and the anticipated safe duration of endurance exercise (St Clair-Gibson and Noakes, 2004).

The proposal that the termination of endurance exercise is a conscious decision determined by perception of effort and potential motivation does not exclude the possibility that endurance performance may be influenced non-consciously. In fact, research over the last three decades has illustrated a variety of contexts in which human behavior can be altered by non-conscious psychological manipulations. Of particular relevance to the psychobiological model of endurance performance are studies showing that subliminal reward priming (Pessiglione et al., 2007; Bijleveld et al., 2010), non-consciously activated goal pursuit (Bargh et al., 2001), subliminal affective priming (Silvestrini and Gendolla, 2011b), and non-consciously activated motivation (Banting et al., 2011) can influence effort. Some of these non-conscious psychological manipulations have been shown to influence effort and performance during physical tasks employing small muscle groups (Pessiglione et al., 2007; Aarts et al., 2008; Radel et al., 2009), cycling exercise (Banting et al., 2011) and rowing exercise (Hodgins et al., 2006). However, the effects of priming with subliminal visual cues on perception of effort and performance during whole-body endurance exercise are currently unknown.

The capacity of the non-conscious perceptual system is considerably large in humans when compared to the limited capacity to attend to conscious information (Dijksterhuis and Nordgren, 2006). Hence, only a trivial amount of momentary information is brought to conscious attention. This means that the majority of this momentary information is processed non-consciously (Merikle et al., 2001). Furthermore, this non-consciously processed information can influence human behavior in a manner that resembles conscious awareness of the same information (Bargh et al., 2001; Pessiglione et al., 2007).

Approximately 90% of the human capacity to process non-conscious information is occupied by the visual system (Dijksterhuis and Nordgren, 2006). Consequently, non-conscious visual cues in particular may have a substantial effect on human behavior. In conjunction with this, a variety of visual cues exist within sporting environments. These range from the words and pictures that are displayed on advertisement hoardings to the facial expressions of competitors, team-mates, and even spectators. Indeed, research has demonstrated that tournament favorites are more prone to choking when a trophy is on display during a competitive final (Bijleveld et al., 2011). The possibility that these visual cues may non-consciously impact upon perception of effort and performance during whole-body endurance exercise therefore has considerable implications for endurance athletes.

Interestingly, non-conscious manipulation of visual cues related to affect and action in the form of subliminal priming has been shown to influence effort during cognitive tasks within the framework of motivational intensity theory. For instance, individuals subliminally primed with happy faces exerted greater effort during challenging cognitive tasks in comparison to when primed with sad faces (Silvestrini and Gendolla, 2011b). Furthermore, subliminal priming with action words enhanced participant willingness to exert effort during a cognitive task whereas subliminal priming with inaction words led to premature effort withdrawal during the same task (Gendolla and Silvestrini, 2010).

Although it is evident that subliminal priming with visual cues related to affect and action can alter effort during cognitive tasks, the effects of such non-conscious visual cues on perception of effort and endurance performance are currently unknown. Establishing these effects is important for endurance athletes and would build on the recognized associations between affective states and endurance performance (Lane et al., 2010) and the links between action words and basic motor activity such as chewing (Albarracín et al., 2008).

The current investigation consists of two experiments. The aim of Experiment 1 was to establish the effects of subliminal priming with affective facial expressions (happy and sad faces) on rating of perceived exertion (RPE) and endurance performance. The aim of Experiment 2 was to establish the effects of subliminal priming with action and inaction words on RPE and endurance performance. Experiment 1 utilized a traditional group design whereas Experiment 2 employed a single-subject design. The latter was used to illustrate the application of randomization tests to assess the effects of non-conscious psychological manipulations in individual athletes as this approach may have important practical uses (see Section General Discussion). In both experiments a TTE test was used to establish the effects of each subliminal priming procedure on RPE and endurance performance without the confounding effect of individual pacing (Hopkins et al., 2001). This test has previously been shown to be a sensitive measure of endurance performance during cycling exercise (Amann et al., 2007).

EXPERIMENT 1: SUBLIMINAL PRIMING WITH HAPPY OR SAD FACES

INTRODUCTION

A clear relationship exists between affective states and sports performance, with positive affect generally associated with better performance and negative affect generally associated with poorer performance (Beedie et al., 2000; Leunes, 2000; Davis et al., 2010). In particular, one aspect of this research has established that affect is related to endurance performance (Lane et al., 2010; Renfree et al., 2011). Despite the widely accepted link between affect and endurance performance (Lane et al., 2012; Stanley et al., 2012), the manner in which endurance performance may be influenced by non-conscious affective cues is still unknown. Based on the psychobiological model of endurance performance, the hypotheses of Experiment 1 were that RPE would be reduced and TTE increased when individuals are subliminally primed with happy faces compared to sad faces during cycling exercise.

MATERIALS AND METHODS

Participant characteristics and ethics

Fourteen healthy and recreationally trained individuals volunteered to take part in the study. One female participant was excluded due to a computer malfunction that revealed one affective facial expression during the final visit. Hence 13 participants were included in the final data analysis [7 males, mean ± *SD*, age 20.1 ± 1.5 years, peak power output (PPO) 328 ± 54 W, maximum oxygen uptake ($\dot{V}o_{2\,max}$) 60.4 ± 6.9 ml·kg^{-1} · min^{-1}; 6 females, mean ± *SD*, age 21.0 ± 1.6 years, PPO 233 ± 34 W, $\dot{V}o_{2\,max}$ 49.2 ± 6.5 ml· kg^{-1} · min^{-1}]. Participants were engaged in endurance exercise on a minimum of one occasion per week. The study was approved by the ethics committee of the School of Sport, Health and Exercise Sciences (SSHES), Bangor University. Accordingly, prior to taking part all participants completed an informed consent form along with a standard medical questionnaire to disclose their present state of health. Before providing informed consent, participants received an overview of the procedures and requirements of the study and were informed that it was a reliability study testing the accuracy of wireless electroencephalography in detecting the neural responses to unanticipated computer stimuli. Consequently, participants were naive to the true aims of the study until its cessation. They were then debriefed and requested not to discuss it further. A payment of £30 (approximately $45/€35) was given to all participants for their involvement.

Experimental design and procedures

The experiment consisted of a single blind, randomized and counterbalanced crossover design in which all participants visited the laboratory on four separate occasions. All exercise tests were conducted at the same location, at a similar time of day, on the same electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, Netherlands). Saddle and handlebar specifications on the cycle ergometer were adjusted to suit the preference of each participant. These specifications were then maintained for every visit thereafter.

During Visit 1, each participant completed the informed consent questionnaire and a checklist to ensure compliance with pre-task instructions; anthropometric measurements were then recorded. After this, an incremental ramp test was carried out on the cycle ergometer to establish PPO and $\dot{V}o_{2\,max}$. The incremental ramp test began with a 2 min rest after which power output was increased by 25 W every minute until exhaustion. Exhaustion was operationally defined as the point at which either the participant voluntarily terminated the test or cadence had fallen below 60 revolutions per minute (RPM) for five consecutive seconds despite strong verbal encouragement. The cycle ergometer was set in hyperbolic mode, which allows the power output to be set independently of pedal frequency over a range of 30–120 RPM and the participant was instructed to remain in the saddle at all times. $\dot{V}o_{2\,max}$, defined as the highest oxygen uptake measured during the test over a 15 s average, was measured breath by breath via a computerized metabolic gas analysis system (Metalyzer 3B, Cortex Biophysik, Leipzig, Germany) connected to an oro-(mouth) mask (7600 series, Hans Rudolph, Kansas City, MO, USA). The device was calibrated before each test using a known concentration of gases and a 3.0 liter calibration syringe (Series 5530, Hans Rudolph). Heart rate was recorded 15 s from the end of the 2 min rest using wireless chest strap radio telemetry (S610, Polar Electro, Kempele, Finland) and was measured every minute during the test thereafter. During the incremental ramp test, subjects were familiarized with RPE (see Section Rating of Perceived Exertion).

Visit 2 was a familiarization session in which participants completed all questionnaires (see Section Psychological Questionnaires) and the TTE test to be used during Visits 3 and 4. Upon arrival for Visit 3 participants completed mood and motivation questionnaires followed by the TTE test. For this test, participants were positioned on the cycle ergometer (set to hyperbolic mode) and instructed to remain in the saddle at all times. The test began with a 3 min warm up at 30% of the participants PPO. After 3 min the power output was automatically increased to a power output corresponding to 65% PPO. Pedal cadence was freely chosen between 60–100 RPM and was recorded every minute during the test, as was heart rate (see Section Additional Physiological Measures). RPE was recorded at 2 min intervals during the test (see Section Rating of Perceived Exertion). TTE was defined as the time accrued from the onset of 65% PPO until the point at which either the participant voluntarily terminated the test or pedal cadence had fallen below 60 RPM for five consecutive seconds. No verbal encouragement was provided at any point during the TTE test to avoid experimenter bias. Furthermore, to avoid bias from facial mimicry, the experimenter stood behind participants at all times (Tassinary et al., 2007). Exactly 3 min after the cessation of the TTE test, participants provided an earlobe sample of whole fresh blood for lactate analysis (see Section Additional Physiological Measures).

Throughout the TTE test participants were exposed to a scanning visual vigilance task (see Section Scanning Visual Vigilance Task). This computerized cognitive task commenced at the onset of the TTE test and stopped at exhaustion. Corresponding to a randomized and counterbalanced order, subjects were allocated to priming with either happy or sad faces which were subliminally delivered within the scanning visual vigilance task for the duration of the TTE test (see Section Subliminal Priming Procedure). During the TTE test the computer screen was placed at eye level 60 cm away from participants. After the TTE test and the blood sample, participants completed the mood questionnaire for the second time.

All procedures during Visit 4 were identical to Visit 3, other than participants being subliminally primed with the alternative affective facial expression. At the end of Visit 4, participants underwent a standardized funneled debriefing procedure (Bargh and Chartrand, 2000). This was to probe for interpretation of the experimental hypotheses and awareness of the subliminal visual cues (see Section Funneled Debriefing Procedure). If any participants alluded to a face within or before the black and white pattern they were further probed for gender, facial expression and any other details. After being fully debriefed, participants were thanked and then received their payment.

The two experimental visits were separated by a minimum of 5 days and a maximum of 14 days. During this time, individuals were instructed to maintain their normal training program. As requested prior to each visit, participants preserved similar dietary patterns during the preceding 24 h while consuming an amount of water equivalent to least

35 ml·kg^{-1} body weight and attaining at least 7 h of sleep the night before. Participants also avoided any heavy exercise in the 24 h prior to testing and refrained from the consumption of caffeine and nicotine 3 h before each exercise test. Finally, participants voided before all exercise tests and performed them in similar clothing during every visit. Participants remained unaware of their TTE for the familiarization visit and for Visits 3 and 4 until the final debriefing procedure.

Scanning visual vigilance task

The scanning visual vigilance task developed by Lieberman et al. (1998) was used in order to deliver subliminal visual cues related to affect during the TTE test. As mental fatigue has been shown to affect RPE and endurance performance (Marcora et al., 2009), this task was selected to minimize the cognitive demands imposed upon participants during the TTE test. Participants were therefore simply requested to focus on the computer screen at all times and informed that a green circle of 3 cm diameter would randomly appear somewhere on the screen. The time that elapsed between each appearance of the circle was no shorter than 45 s, and no longer than 90 s. Participants were instructed to carry on cycling whilst maintaining focus upon the screen, but no response was required when the circle appeared. Each 3 cm green circle appeared at an identical time and screen location for all participants across both visits.

Subliminal priming procedure

Subjects were subliminally primed during the scanning visual vigilance task throughout each TTE test. One prime was presented sequentially every 4996 ms. Each prime sequence consisted of a white fixation cross that was displayed on a black background in the center of the computer screen (1000 ms). This was instantly followed by a facial expression (16 ms) that was backward masked by a briefly flashed black and white pattern (130 ms). Following the backward mask, the screen either remained black (3850 ms) or alternatively a green circle of 3 cm diameter appeared against the black background in a random location (3850 ms). The next prime sequence was commenced immediately after this. In order to prevent habituation to the affective facial expressions, two thirds of the prime sequences consisted of a neutral face with the remaining one third consisting of the relevant affective facial expression (Silvestrini and Gendolla, 2011a). So as participants were exposed to the affective facial expressions throughout the TTE test, it was ensured that two affective facial expressions were presented within every six prime sequences. The remaining four primes within each six prime sequence consisted of neutral faces. The affective facial expressions consisted of a front perspective black and white human image (see **Figure 1**) taken from the Averaged Karolinska Directed Emotional Faces (ADKEF) database (Lundqvist and Litton, 1998). Half of the faces were male (MNES, MSAS, MHAS) and the other half were female (FNES, FSAS, FHAS). The priming program was generated in E-prime software (E-Prime, Psychology Software Tools, Pittsburgh, PA, USA) and the primes were presented on a 19′ computer monitor with an aspect ratio of 16:9, a refresh rate of 60 Hz, and a 1280 × 720 pixel array.

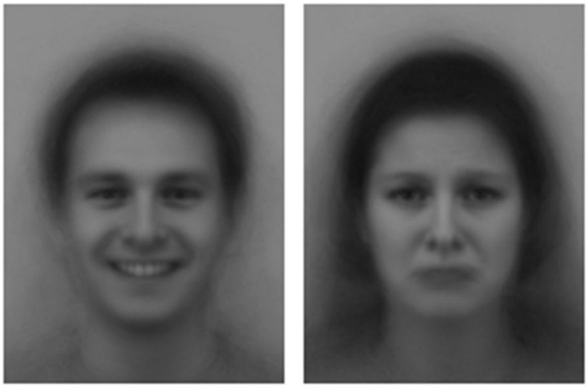

FIGURE 1 | An example of the happy and sad facial expressions used for subliminal priming during the time to exhaustion test.

Funneled debriefing procedure

The funneled debriefing procedure was administered as a manipulation check to ensure that participants were not consciously aware of the affective facial expressions during the subliminal priming procedure. This method was adopted from previous recommendations from subliminal priming research (Bargh and Chartrand, 2000) and consisted of six questions about the subliminal priming procedure. These questions investigated participant perspectives on: (1) the purpose of the experiment; (2) any curiosities during the experiment; (3) the relation between the TTE test and the computer task; (4) the effect of the computer task on the TTE; (5) the reason for the black and white pattern that acted as the backward mask; and (6) anything specific before, during, or after the presentation of the black and white pattern.

Rating of perceived exertion

Perception of effort was measured using the Category Ratio 10 (CR10) scale developed by Borg (1998) using standardized instructions and verbal anchors for RPE. Low (0.5) and high (10) anchors were established during the incremental ramp test using standard procedures (Noble and Robertson, 1996). A CR10 scale was provided to all participants after Visit 1, and standardized instructions for RPE were repeated prior to each TTE test with the emphasis that each rating should be based upon the leg effort required to cycle and how heavy is the breathing as opposed to any leg pain or discomfort that may be associated with cycling exercise. Furthermore, participants were informed that they were free to rate perceived exertion above 10 if they perceived effort to be higher than the maximal effort perceived during the incremental ramp test. During the TTE test, the CR10 scale was automatically presented on the computer screen every 2 min. Participants were requested to read out the number that corresponded to their present rating upon every presentation of the scale. For each measurement, the CR10 scale remained on screen for 3850 ms and always replaced the black screen that appeared immediately after the backward mask.

Additional physiological measures

Heart rate was recorded throughout the TTE test using wireless chest strap radio telemetry (S610, Polar Electro, Kempele, Finland). Before testing, the chest strap was dampened and securely fastened to the participant's chest according to the manufacturer's guidelines. Lactate concentration was measured by collecting 5 μl of whole fresh blood from the earlobe 3 min after the TTE tests. Each blood sample was immediately analyzed using a calibrated device (Lactate Pro LT-1710, Arkray, Shiga, Japan).

Psychological questionnaires

In order to evaluate differences in conscious affective state before and after the TTE test, mood was assessed using two self-reported items of the positive (*happy and joyful*) and negative (*sad and depressed*) hedonic tone scales of the U-WIST mood adjective checklist developed and validated by Matthews et al. (1990). The four mood items were rated according to momentary affective state (*right now, I'm feeling*) on a 7-point Likert-type scale ranging from (1) *not at all*, to (7) *very much*. These items have been used elsewhere in order to establish conscious affective state during similar subliminal priming studies (Silvestrini and Gendolla, 2011b; Freydefont et al., 2012). Consistent with this previous research, a global mood rating was established by summating the positive hedonic tone scale items with the reverse scored negative hedonic tone scale items. Motivation was measured prior to the TTE test via the success motivation (example item; *The task will bring out my competitive drive*) and intrinsic motivation (example item; *Doing the task is worthwhile*) scales developed and validated by Mathews et al. (2001). Each scale consists of seven items responded to on a 5-point Likert-type scale (0 = *not at all*, 1 = *a little*, 2 = *moderately*, 3 = *quite a bit*, 4 = *extremely*).

Statistical analyses

Unless otherwise noted, data are shown as mean ± *SD*. All data were first checked for normality using the Shapiro-Wilk test. Following this, paired sample *t*-tests were used to assess the effect of visit order on TTE, and the effects of subliminal affective priming on TTE, mean cadence, pre-exercise global mood rating, intrinsic motivation, success motivation, and various measures at exhaustion (RPE, heart rate, and blood lactate concentration). A 2 × 2 (Condition × Time) fully repeated measures analysis of variance (ANOVA) was used to assess the effects of subliminal affective priming on global mood ratings measured before and after the TTE test. A 2 × 5 (Condition × Iso-time) fully repeated measures ANOVA was used to assess the effects of subliminal affective priming on RPE and heart rate measured at 0%, 25%, 50%, 75% and 100% of iso-time during the TTE test. To obtain these iso-time data, the value of each parameter at 100% iso-time was established by identifying the shortest TTE accomplished by each individual over their two tests. The value for each variable attained during the final full minute of the shortest TTE test was then compared to the value attained during the equivalent minute of the longer TTE test. The minute identified as 100% iso-time was multiplied by 0.5 and rounded to the nearest time of rating where necessary to attain the value corresponding to 50% iso-time. To establish 25% iso-time values, the minute identified as 100% iso-time was multiplied by 0.25. To establish 75% iso-time the minute identified as 100% iso-time was multiplied by 0.75. Iso-time values for 0% were attained by comparing values for the first full minute of each TTE test. For all ANOVAs, if assumptions of sphericity were violated, the Greenhouse-Geisser correction was used while Tukey's HSD *post hoc* tests were calculated where appropriate. Standardized Cohen's *d* values were calculated using Morris and DeShon's (2002) equation 8 to provide an estimate of effect size. Thresholds for small, moderate, and large effect sizes were set at 0.2, 0.5, and 0.8, respectively (Cohen, 1988). Precision of the estimate was established by ± 90% confidence intervals were relevant (Hopkins et al., 2009). This indicated the plausible range within which the population effect for a measure may reside (Cumming, 2014). For all data analysis, statistical significance was set at $p < 0.05$ (two-tailed) and conducted using the statistical package for social sciences (SPSS version 16).

RESULTS

Manipulation check

During the funneled debriefing procedure, the description given by all participants regarding their understanding of the study rationale conformed to the study rationale that they were provided with before the experiment. No participant was able to report anything unusual that was related to the real experimental manipulation, no participant suggested that the computer screen affected what they did during the TTE test and no participant was able to decipher the real reason for the black and white patterned backward mask. Three participants mentioned a possible brief facial silhouette on one occasion within the flashed black and white pattern that acted as the backward mask. However when probed further, no participant was able to elaborate on the facial expression of this silhouette. As no participant was suspicious of the study's true purpose at its culmination and no participant was aware of any facial expression within or prior to the flashed backward mask, this was considered to provide sufficient evidence of a successful experimental manipulation.

Effects of subliminal affective priming on mood and motivation

We created separate global mood ratings for pre-exercise and post-exercise mood by adding the positive hedonic tone scale items to the reverse scored negative hedonic tone scale items (**Table 1**). The global mood ratings between conditions were not significantly different pre-exercise, $t_{(12)} = 0.48$, $p = 0.64$. In addition, neither subliminal affective priming (main effect of condition: $F_{(1,12)} = 0.73$, $p = 0.41$) nor the TTE test (main effect of time: $F_{(1,12)} = 0.17$, $p = 0.69$) affected the global mood ratings. There was also no significant condition x time interaction on this measure of mood ($F_{(1,12)} = 0.14$, $p = 0.71$). These findings indicate that subliminal affective priming did not affect conscious affective state either before or after the TTE test.

Similar to mood, ratings for success motivation (happy faces = 18.4 ± 5.1, sad faces = 17.1 ± 5.6, $t_{(12)} = 1.73$, $p = 0.11$) and intrinsic motivation (happy faces = 23.2 ± 3.1, sad

Table 1 | Mean ± *SD* of global mood ratings for U-WIST mood adjective checklist.

	Pre-exercise	Post-exercise
Happy	23.2 ± 2.6	23.6 ± 2.7
Sad	22.9 ± 2.7	23.0 ± 2.3

faces = 22.2 ± 2.6, $t_{(12)} = 1.95$, $p = 0.07$) were not statistically different between conditions.

Effect of subliminal affective priming on TTE

As predicted, subliminal affective priming had a significant effect on TTE, with participants cycling for 178 s (12%) longer when they were subliminally primed with happy faces (1519 ± 787 s) in comparison to when they were subliminally primed with sad faces (1342 ± 585 s), $t_{(12)} = -2.28$, $p = 0.04$, $d = 0.88$, 90% CI [38 s, 318 s]. As shown in the condition-by-condition scatterplot (see **Figure 2**), eight individuals performed greater on the TTE when they were subliminally primed with happy faces compared to sad faces. No order effect was present for TTE across visits, $t_{(12)} = -0.65$, $p = 0.53$.

Effects of subliminal affective priming on mean cadence and heart rate, blood lactate concentration and RPE at exhaustion

At exhaustion, there were no significant differences between subliminal priming with happy and sad faces in heart rate, blood lactate concentration, and RPE (**Table 2**). The latter finding indicates that participants were willing to exert a maximal effort in both conditions. Mean cadence was however greater when participants were subliminally primed with happy faces compared to when subliminally primed with sad faces. Albeit statistically significant, this difference would be considered marginal.

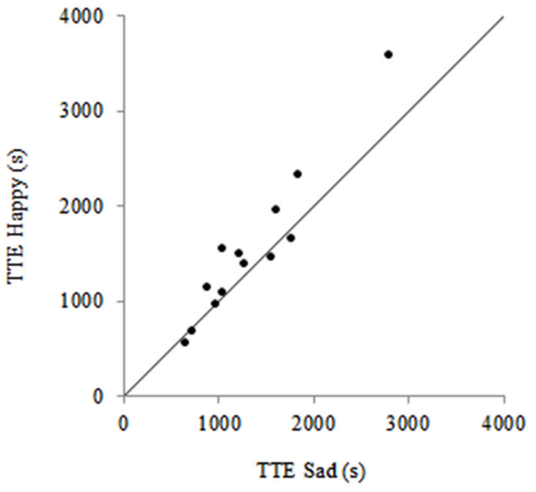

FIGURE 2 | Scatterplot showing individual time to exhaustion (TTE) data following subliminal priming with happy faces and subliminal priming with sad faces. The points above the identity line represent a greater TTE following subliminal priming with happy faces compared to sad faces.

Table 2 | Mean ± *SD* of mean cadence, and heart rate, blood lactate concentration and RPE at exhaustion.

	Sad	Happy	*p*-value
Blood [la] (mmol·l)	7.13 ± 1.86	6.97 ± 2.51	0.60
Heart Rate (beats·min^{-1})	180 ± 10	181 ± 10	0.53
RPE (0–10+)	9.92 ± 0.28	9.96 ± 0.32	0.33
Mean Cadence (RPM)	75.8 ± 4.7	78.0 ± 3.3	0.01

Note. Blood [la] = blood lactate concentration; RPE = rating of perceived exertion; RPM = revolutions per minute.

Effects of subliminal affective priming on heart rate and RPE during the TTE test

RPE increased significantly during the TTE test (main effect of iso-time: $F_{(2.13,25.50)} = 152$, $p = 0.001$). However, RPE was significantly lower following subliminal priming with happy faces compared to subliminal priming with sad faces (main effect of condition: $F_{(1,12)} = 5.29$, $p = 0.04$). Despite this, no significant condition × iso-time interaction ($F_{(4,48)} = 1.43$, $p = 0.24$) was evident (see **Figure 3**).

Heart rate increased significantly during the TTE test (main effect of iso-time: $F_{(1.22,14.69)} = 127$, $p < 0.001$) however there was no significant main effect of condition ($F_{(1,12)} = 0.19$, $p = 0.67$) or condition x iso-time interaction ($F_{(1.98,23.74)} = 1.08$, $p = 0.36$) with a mean heart rate of 171 ± 10 beats·min^{-1} when participants were subliminally primed with happy faces, compared to a mean of 170 ± 10 beats · min^{-1} when participants were subliminally primed with sad faces.

DISCUSSION

The findings that non-conscious visual cues related to affect can alter perception of effort and performance during whole-body endurance exercise are in line with previous studies that have effectively used similar subliminal priming procedures to manipulate performance (Freydefont et al., 2012) and effort (Silvestrini and Gendolla, 2011b) during cognitive tasks. The fact that the positive effect of subliminal priming with happy faces on TTE was associated with a reduction in RPE when compared to subliminal priming with sad faces is also consistent with the psychobiological model of endurance performance which posits that, in well-motivated individuals, the primary factor determining endurance performance is perception of effort.

The present findings provide experimental evidence to support the hypothesis that positive affect is associated with better sport performance and negative affect is associated with poorer sport performance. This is important as support to this hypothesis is seemingly limited to correlational findings (Lane et al., 2012; Stanley et al., 2012) and indirect experimental manipulations (Astorino et al., 2012; Terry et al., 2012). As such, the present research provides the first evidence that affective cues can influence perception of effort and endurance performance when they are manipulated directly. Even more importantly, the current findings considerably extend this research area to show that perception of effort and endurance performance can be altered by affective visual cues that occur outside of conscious awareness.

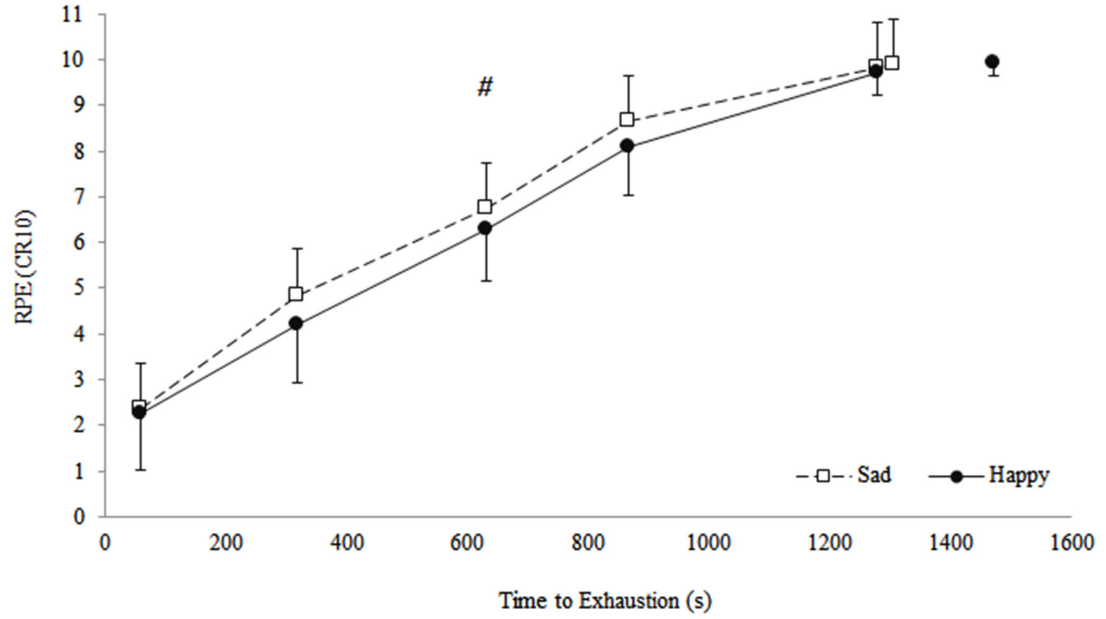

FIGURE 3 | Effect of subliminal priming with happy or sad faces on rating of perceived exertion (RPE) at 0%, 25%, 50%, 75%, 100% iso-time, and at exhaustion during the time to exhaustion test. Data are presented as mean (± *SD*). # Indicates significant main effect of condition at iso-time ($p = 0.04$).

EXPERIMENT 2: SUBLIMINAL PRIMING WITH ACTION OR INACTION WORDS

INTRODUCTION

The aim of Experiment 2 was to replicate the findings of Experiment 1 with a different type of subliminal visual cues: action and inaction words. This type of non-conscious visual cues is relevant for a number of reasons. Specifically, the effects of subliminal priming with action or inaction words on perception of effort and endurance performance may be mediated by alterations in premotor and motor areas of the brain. Activity of these cortical areas during muscle contractions is associated with perception of effort in humans (de Morree et al., 2012) and action words have shown to activate premotor and motor areas of the brain (Hauk et al., 2004) showing that the cortical systems for language and action are reciprocally connected (Pulvermüller, 2005). Supportively, in comparison to subliminal inaction words, subliminal action words have been shown to prompt greater activity on basic motor tasks such as chewing (Albarracín et al., 2008). Moreover, subliminal action and inaction words have recently been shown to alter effort during cognitive tasks (Gendolla and Silvestrini, 2010). Because perception of effort is thought to be generated by neurocognitive processing of corollary discharges from premotor and/or motor areas of the brain (Marcora, 2009; de Morree et al., 2012), evidence that action words can affect these cortical areas (Hauk et al., 2004) provides some neurobiological rationale for an effect of subliminal action words on perception of effort and, thus, endurance performance. To test these hypotheses, Experiment 2 implemented a relatively novel single subject experimental design (Dugard et al., 2012) to assess the effects of subliminal priming with action and inaction words on perception of effort and endurance performance during cycling exercise. Therefore, the hypotheses of this experiment were that RPE would be reduced and TTE increased when individuals are subliminally primed with action words compared to inaction words.

MATERIALS AND METHODS

Participant characteristics and ethics

One healthy male participant (age 22 years, PPO 287 W, $\dot{V}O_{2\,max}$ 58.3 ml·kg^{-1} · min^{-1}) volunteered to take part in the study. The participant was an experienced endurance athlete having trained and competed at a regional level in endurance sports for 4 years at the time of the study. Accordingly the participant was regularly engaged in endurance exercise (running and cycling) on at least two occasions per week and continued to also frequently take part in competitive endurance events. The participant received £150 (approximately $250/€180) for his involvement in the study. The study was approved by the ethics committee of the SSHES, Bangor University. Prior to taking part the participant completed an informed consent form along with a standard medical questionnaire to confirm his present state of health. The participant was provided with a detailed overview of all procedures and requirements of the study before its commencement and was informed that the study was a reliability study designed to test the ability of wireless electroencephalography to accurately detect the neural responses to unanticipated computer stimuli. Consequently, the participant was naive to the true aims and hypotheses until the cessation of the study, at which point he was debriefed about its genuine rationale.

Experimental design

The experiment was a single blind, blocked randomization tests design (Dugard et al., 2012) in which the participant visited the laboratory on 14 occasions. Visits 1 and 2 involved an incremental ramp test and a familiarization session respectively and Visits 3 to 14 were comprised of the 12 experimental visits. These 12 experimental visits encompassed a crossover design in which the participant was randomly allocated to 6 visits for each of the two experimental treatment conditions (subliminally primed action vs. inaction words). The order of treatment visits was randomized in three blocks of four, categorized in sequence as Blocks 1, 2, and 3. Accordingly, within each block the individual was randomly allocated to two visits for each treatment. This blocked procedure was performed to provide further control over the training effect that consecutive TTE tests may elicit along with other confounding order effects such as learning and demotivation (Dugard et al., 2012). The blocks of randomized visits were merged in numerical sequence to create one complete experimental arrangement of treatments across the 12 visits (*Block 1: action, inaction, inaction, action; Block 2: inaction, inaction, action, action; Block 3: inaction, action, inaction, action*).

Procedures

All exercise tests were conducted at the same location, at a similar time of day, on the same electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, Netherlands). Saddle and handlebar specifications on the cycle ergometer were adjusted on the first visit to suit participant preference and these specifications were then maintained for every visit. Visit 1 consisted of an incremental ramp test to establish PPO and $\dot{V}o_{2\,\mathrm{max}}$. All procedures for this incremental test were identical to those in Experiment 1. Visit 2 consisted of a familiarization session in which the participant completed all questionnaires (see Section Psychological Questionnaires) and the TTE test that was to be used during the 12 experimental visits. This familiarization session was also identical to the familiarization session outlined in Experiment 1. For the subsequent 12 visits, upon arrival the participant first completed mood and motivation questionnaires (see Section Psychological Questionnaires), this was followed by the TTE test. Other than the randomly allocated subliminal word primes delivered during the 12 TTE tests, the procedure for all 12 of these tests was identical to the TTE tests used in Visits 3 and 4 of Experiment 1. At the end of Visit 14 the participant underwent a standardized funneled debriefing procedure (Bargh and Chartrand, 2000) to probe for interpretation of the experimental hypotheses and awareness of the subliminal word primes. After being fully debriefed the participant was thanked and then received his payment.

Visits 1, 2, and 3 were separated by a minimum of 7 days each, while all visits between Visits 3 and 14 were separated by a minimum of 6 days and a maximum of 15 days. All pre-visit instructions were the same as those for Experiment 1. The participant remained unaware of his TTE value for the familiarization visit and for every subsequent visit until the final debriefing procedure.

Subliminal priming procedure

In conjunction with visit allocation, action or inaction words were subliminally primed within the computerized scanning visual vigilance task for the duration of each TTE test. The procedure for the scanning visual vigilance task was identical to that of Experiment 1 other than the fact that subliminally primed words replaced the subliminally primed affective facial expressions that were used in Experiment 1. During the subliminal priming procedure, a word prime sequence was presented serially every 4996 ms. Each prime sequence first consisted of a white fixation cross that was displayed on a black background in the center of the screen (1000 ms). This was instantly followed by a word prime (16 ms) that was backward masked by a random letter sequence (130 ms). This random letter sequence always consisted of the letters MZKGWB and appeared after every word prime.

Following the backward mask, the screen either remained black (3850 ms) or alternatively a green circle of 3 cm diameter appeared against the black background in a random location on the screen (3850 ms). The next word prime sequence commenced immediately after. To prevent habituation to the subliminal word primes, two thirds of the primes consisted of non-word primes with the remaining one third consisting of the word primes (Silvestrini and Gendolla, 2011a). To ensure that exposure to the subliminal word primes occurred throughout each TTE test, two word primes were randomly presented within each six prime sequence. The remaining four primes within each six prime sequence therefore consisted of the non-word primes.

The word primes were obtained from the empirically derived Computerized Edinburgh Associative Thesaurus (Kiss et al., 1973). The selected action primes consisted of the words *ACTION*, *GO*, *LIVELY* and *ENERGY*. The inaction primes consisted of the words *STOP*, *TOIL*, *SLEEP*, and *TIRED*. The non-word primes were created by re-arranging the letter order of the action and inaction words. The word primes, non-word primes, and the backward mask were all presented in white capital letters of size 125 calibri font in the center of the screen and against a black background. The priming program was generated in E-prime software (E-Prime, Psychology Software Tools, Pittsburgh, PA) and the primes were presented on a 19′ computer monitor with an aspect ratio of 16:9, a refresh rate of 60 Hz and a 1280 × 720 pixel array.

Funneled debriefing procedure

The funneled debriefing procedure (Bargh and Chartrand, 2000) was the same as Experiment 1 other than specific alterations to Questions 5 and 6 which were adjusted to: (5) the reason for the random letter string that acted as the backward mask; and (6) anything specific regarding the letters.

Rating of perceived exertion

The procedures used to measure RPE were identical to those in Experiment 1 except that RPE was measured at 1 min intervals during the TTE test.

Psychological questionnaires

The Brunel mood scale (BRUMS) was used to assess mood before the TTE test. This measure of mood has been validated for use with adult populations (Terry et al., 2003). The measure is comprised of six subscales (anger, confusion, depression, fatigue, tension, and vigor) with four items per subscale. Items were answered on a 5-point Likert-type scale (0 = *not at all*, 1 = *a little*, 2 = *moderately*, 3 = *quite a bit*, 4 = *extremely*). The procedures that were used to measure motivation prior to the TTE test were identical to those in Experiment 1.

Statistical analyses

Unless otherwise noted, data are shown as mean ± *SD*. Randomization tests (Dugard et al., 2012) were used to assess for mean differences between treatments (action vs. inaction words) in TTE, mean cadence, all BRUMS subscales, success and intrinsic motivation, and various measures at exhaustion (RPE, heart rate, and blood lactate concentration). Randomization tests were also used to assess differences between conditions for RPE and heart rate at the 15th minute of the TTE test. The 15th minute was selected as this represented the final full minute of the shortest TTE over the 12 Visits.

For each randomization test, in order to test for statistical significance, mean values for each treatment condition were first calculated. The difference between these means was then obtained. These values provided the true experimental difference between treatments for each dependent variable. The randomized order of experimental treatments across the 12 visits represented one of many possible ways in which the treatment visits could have been arranged. Using a pre-designed macro (Dugard et al., 2012) the raw data from the 12 experimental treatment visits was randomly rearranged 2000 times to coincide with alternative visits in the original treatment allocation. For each of these 2000 rearrangements, only the raw data from treatment conditions was randomly rearranged with the allocated treatment order of the respective 12 experimental visits remaining the same. Specifically, this meant that the raw data for each visit was randomly swopped between the allocated treatment visits two thousand times. Due to the present design, this procedure was performed only on a within block basis. Hence for example, a raw value from Block 1 could not be rearranged to a visit in Blocks 2 or 3. Rearranging the raw data in proximity to the assigned visits in this manner permitted the calculation of a mean difference between treatment conditions for each of the 2000 treatment rearrangements. In order of magnitude from high to low, the true mean difference was then ranked amongst the 2000 mean differences that were obtained from the treatment rearrangements. Statistical significance was obtained if the mean difference for the experimental data was greater than 95% of the mean differences acquired from the 2000 treatment rearrangements. Statistical significance was set at $p < 0.05$ (one-tailed) for TTE and RPE and $p < 0.05$ (two-tailed) for all other analyses. All data analysis was conducted using a specified macro (Dugard et al., 2012) in Microsoft Excel 2010.

RESULTS

Manipulation check

A qualitative evaluation of the funneled debriefing procedure indicated that the participant believed the cover rationale for the study to be genuine throughout. The participant also did not detect any subliminally primed action and inaction words during the 12 visits. The participant therefore remained naive to the true experimental hypotheses during the investigation.

Effects of subliminal priming with action or inaction words on mood and motivation

A randomization test for each BRUMS subscale revealed no significant differences in pre-exercise mood between conditions (see **Table 3**). Similarly, no significant differences were evident between conditions for ratings of success or intrinsic motivation related to the upcoming TTE test.

Effects of subliminal priming with action or inaction words on TTE, mean cadence, and heart rate, blood lactate concentration and RPE at exhaustion

The participant cycled for 399 s longer when subliminally primed with action words in comparison to inaction words (see **Table 4**). This difference of 399 s between conditions was ranked within the top 3.6% of means that were obtained from the 2000 alternative random treatment arrangements. TTE was therefore significantly greater following subliminal priming with action words vs. inaction words ($p = 0.04$). To make sure that these findings were not affected by the extreme value observed during Visit 2, a second analysis was conducted by replacing this extreme value with the highest value from the corresponding condition in the same block. Even when using this conservative approach, TTE remained significantly greater following subliminal priming with action words vs. inaction words ($p = 0.05$). Unlike TTE, heart rate, blood lactate and RPE at exhaustion were not significantly different between conditions. Mean cadence during the TTE test was also not significantly different between conditions.

Effects of subliminal priming with action or inaction words on RPE and heart rate during the TTE test

Randomization tests between conditions at iso-time (15th minute) revealed that RPE was significantly lower ($p = 0.03$) when

Table 3 | Mean ± *SD* participant rating for all Brunel Mood Scale (BRUMS) subscales, and success and intrinsic motivation prior to the time to exhaustion test.

	BRUMS subscales						Motivation	
	Anger	**Confusion**	**Depression**	**Fatigue**	**Tension**	**Vigour**	**Success**	**Intrinsic**
Action	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	2.83 ± 0.75	14.33 ± 1.97	28.00 ± 0.00	28.00 ± 0.00
Inaction	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	4.17 ± 0.75	14.83 ± 0.98	27.67 ± 0.52	28.00 ± 0.00
p =	0.99	0.99	0.99	0.99	0.06	0.49	0.33	0.99

Table 4 | Individual data by block, visit order, and subliminal word primes for TTE, mean cadence, and heart rate, blood lactate concentration and RPE at exhaustion.

Block	Visit	Condition	TTE (s)	HR (beats . min^{-1})	Blood [la] (mmol·l)	Mean Cadence (RPM)	RPE (0-10+)
1	1	A	1772	140	2.2	86.5	10
1	2	I	915	136	2.6	80.6	10
1	3	I	1835	137	3.1	85.1	10
1	4	A	1910	144	2.7	86.9	10
2	5	I	2304	146	2.0	82.3	10
2	6	I	2781	153	2.6	84.8	10
2	7	A	2822	148	1.9	80.7	10
2	8	A	2975	142	2.3	81.9	10
3	9	I	2705	139	1.9	81.1	10
3	10	A	3291	138	2.4	81.0	10
3	11	I	2528	139	2.4	82.2	10
3	12	A	2692	136	1.9	81.9	10
Action (Mean ± SD)			2577 ± 605	141 ± 4	2.23 ± 0.31	83.1 ± 1.4	10 ± 0
Inaction (Mean ± SD)			2178 ± 706	142 ± 7	2.43 ± 0.44	82.7 ± 1.7	10 ± 0

Note. TTE = time to exhaustion; HR = heart rate; Blood [la] = blood lactate concentration; RPM = revolutions per minute; RPE = rating of perceived exertion; A = action words; I = inaction words.

the participant was subliminally primed with action words during the TTE test compared to inaction words (see **Figure 4**). In contrast to RPE, randomization tests revealed that heart rate was not significantly different between conditions at iso-time ($p = 0.35$). Furthermore, there was no significant difference in mean heart rate during the TTE test between conditions ($p = 0.30$) with the participant obtaining a mean heart rate of 138 ± 4 beats·min^{-1} when subliminally primed with action words, compared to a mean of 139 ± 8 beats·min^{-1} when subliminally primed with inaction words.

DISCUSSION

The results of Experiment 2 bolster those of Experiment 1 by demonstrating that non-conscious visual cues related to action were able to significantly alter RPE and TTE for the individual involved in this single-subject randomized experiment. These findings are consistent with the previously reported effects of subliminal priming with action or inaction words on effort during cognitive tasks (Gendolla and Silvestrini, 2010) and provide the first evidence that these effects extend to physical tasks. In addition, this study exhibits the utility of randomization tests as

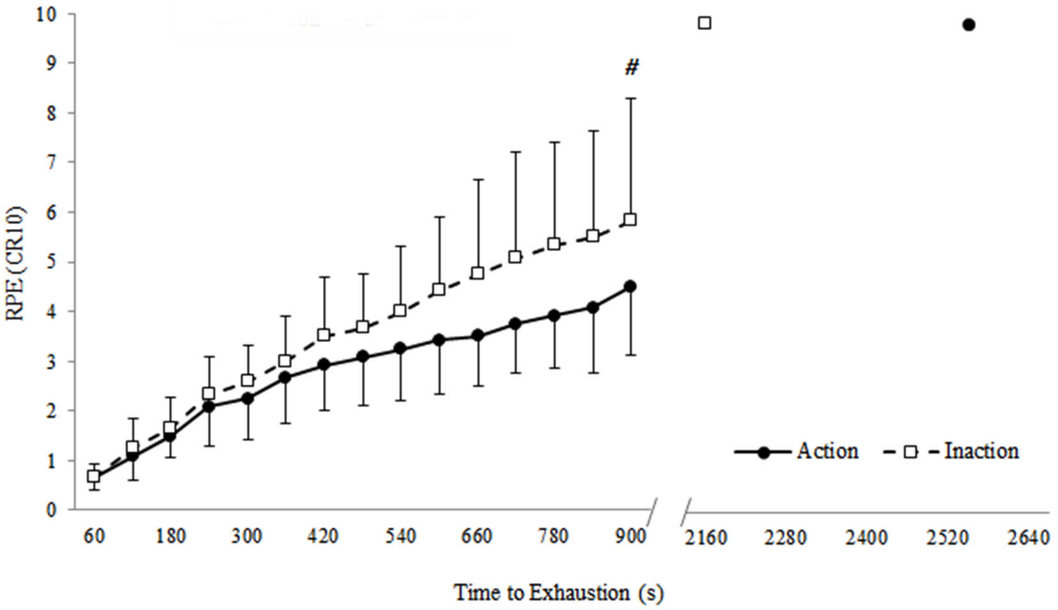

FIGURE 4 | Effect of subliminal priming with action or inaction words on rating of perceived exertion (RPE) at minute 15 of the time to exhaustion tests and at exhaustion. Data are presented as mean (± *SD*). # Indicates significant difference between conditions ($p = 0.03$).

an effective methodological approach to analyse data from single-subject experiments. Such an approach has worthwhile practical and research based implications for scenarios that involve special populations such as elite athletes where assessment of individual responses is essential.

GENERAL DISCUSSION

The purpose of the present research was to investigate the effects of non-conscious visual cues on perception of effort and endurance performance. The two different types of visual cues utilized in Experiments 1 and 2 respectively were able to alter both perception of effort and endurance performance during cycling exercise. Specifically, as hypothesized in Experiment 1, subliminally priming participants with happy faces as they cycled to exhaustion at 65% PPO significantly reduced RPE in comparison to subliminal priming with sad faces. Correspondingly TTE was significantly greater when participants were subliminally primed with happy faces. Similarly, the findings from the single subject approach used in Experiment 2 demonstrated that subliminal priming with action words significantly reduced RPE and enhanced TTE in comparison to subliminal priming with inaction words.

The findings that non-conscious visual cues can affect perception of effort and whole-body endurance performance extend previous reports that non-conscious psychological manipulations have significant effects on effort and behavior during both cognitive and physical tasks (Bargh et al., 2001; Hodgins et al., 2006; Pessiglione et al., 2007; Aarts et al., 2008; Bijleveld et al., 2010; Banting et al., 2011; Silvestrini and Gendolla, 2011b; Freydefont et al., 2012). Gendolla (2000) has previously suggested that affective states influence the appraisal of task demand and the subjective experience of task-related effort. For example, positive moods have been found to reduce appraisals of task demand and experienced effort whereas negative moods have the opposite effects (Gendolla et al., 2001). This corresponds to the predictions made by motivational intensity theory (Brehm and Self, 1989; Wright, 2008). Consequently, lower appraisals of task demand coincide with a reduced experience of effort during objectively easy tasks, whereas effort is more willingly tolerated as task difficulty increases. Conversely, increased appraisals of task demand coincide with an elevated experience of effort during objectively easy tasks, whereas effort is more readily withheld as task difficulty increases (Gendolla et al., 2001). The effect of action and inaction words has also been placed within the context of motivational intensity theory such that action and inaction words are proposed to influence effort as long as task success is regarded as possible and worthwhile (Silvestrini and Gendolla, 2013). Hence primed action words elicit greater effort investment than primed inaction words on cognitive tasks providing that the demands of the task are regarded as possible.

Based on motivational intensity theory, the psychobiological model of endurance performance (Marcora, 2008; Marcora and Staiano, 2010) proposes that individuals will persist with endurance exercise until they reach the maximum amount of effort that they are willing to exert in order to succeed in the task (i.e., potential motivation), or until continuation in the task is perceived as impossible. When one of these two scenarios occurs, the conscious sensation of effort will therefore prompt individuals to voluntarily terminate endurance exercise. In conjunction with the findings of Gendolla et al. (2001) and Silvestrini and Gendolla (2011b), the subliminal priming of happy faces in Experiment 1 therefore likely reduced subjective appraisal of task demand whereas the subliminal priming of sad faces elicited the opposite effect. Consequently, this delayed the point at which a very high perception of effort made continuation in the TTE test seem impossible. In Experiment 2, due to the fixed power output used in the TTE test, it is impossible for individuals to intentionally increase effort. In our study it is therefore likely that action word priming instead permitted the individual to cycle at the same power output for a lower RPE. Alternatively, or concurrently, it is possible that inaction word priming increased the momentary RPE. In either case this would alter the point at which continuation in the task appeared impossible, hence explaining the difference in TTE.

This psychobiological model of endurance performance provides a single theoretical framework to explain the effects of many different physiological and psychological factors known to affect endurance performance. These factors include muscle fatigue (Marcora et al., 2008), muscle damage (Marcora and Bosio, 2007), mental fatigue (Marcora et al., 2009), motivational self-talk (Blanchfield et al., 2014), psychostimulants (Sgherza et al., 2002; Jacobs and Bell, 2004), sleep deprivation (Martin, 1981), inspiratory muscle fatigue (Gething et al., 2004), nutritional supplementation (Blackhouse et al., 2005), and aerobic training (Ekblom and Goldbarg, 1971). Indeed, in all the above examples, changes in endurance performance were associated with changes in RPE. The present findings extend the explanatory power of this model by showing that non-conscious psychological factors may also modify perception of effort and influence the associated decision making process that determine endurance performance.

The significant effects of subliminal visual cues on TTE also challenge the proposal that endurance exercise terminates when the fatigued neuromuscular system (Amann and Dempsey, 2008), or the muscles themselves (Allen et al., 2008; MacIntosh and Shahi, 2011), are no longer able to produce the power/force required by exercise as postulated by the muscle fatigue model of endurance performance. Specifically, it is unlikely that differences in TTE between subliminal priming conditions were mediated by the cardiovascular and metabolic factors commonly associated with muscle fatigue because no significant differences were evident in heart rate or post-exercise lactate in each experiment. Moreover, although mean cadence was different between conditions in Experiment 1, such a marginal difference of two RPM is unlikely to have contributed to changes in motor unit recruitment or cycling efficiency (Dantas et al., 2009). In addition to our physiological measures, pre-exercise mood and motivation were similar between conditions. These findings suggest that these psychological factors did not mediate the effects of subliminal priming on endurance performance. Furthermore, although muscle fatigue was not measured in the present studies, the very nature of subliminal visual cues and their lack of effects on the physiological responses to endurance exercise suggest that an effect on peripheral fatigue is very unlikely. Similarly, there is evidence that cognitive tasks much more demanding than the cognitive task used to provide subliminal visual cues to our subjects do not induce central fatigue (Pageaux et al., 2013). Overall, we believe it is safe to speculate that central and/or peripheral muscle fatigue are unlikely to explain the significant effects of subliminal visual cues on endurance performance, and that a more plausible mechanism is alterations in perception of effort.

The present findings also provide further evidence against one of the main hypotheses of the central governor model of endurance performance: the subconscious brain, based on interoception and previous experience, calculates the maximum time a person can exercise without a catastrophic failure of homeostasis, and regulates RPE and TTE accordingly (St Clair-Gibson and Noakes, 2004). In this regard it is important not to confuse the well-established fact that the brain is capable of processing subliminal visual cues (Pessiglione et al., 2007; Aarts et al., 2008; Silvestrini and Gendolla, 2011b) with the proposal that a subconscious intelligent system regulates neural recruitment of locomotor muscles during endurance exercise to avoid harm to the human (Noakes, 2000; St Clair-Gibson and Noakes, 2004). As shown in the present experiments, subliminal visual cues had significant effects on the conscious sensation of effort which, according to the psychobiological model of endurance performance, determined the different times at which our subjects consciously decided to terminate endurance exercise. On the other hand, it seems highly unlikely that providing subliminal visual cues could affect the physiological condition of the body before and during endurance exercise and, as a result, influence the subconscious and teleoanticipatory calculations made by the central governor about the maximum time our subjects could exercise without a catastrophic failure of homeostasis (Noakes, 2011). Once more, this speculation is supported by the fact that subliminal visual cues did not affect the physiological responses to endurance exercise in our two studies. Therefore, the central governor model does not provide a plausible explanation for the significant effects of subliminal visual cues on perception of effort and endurance performance.

Given the pivotal role played by perception of effort in mediating the effects of subliminal visual cues on endurance performance, it is important to establish the mechanisms that may be responsible for changes in perception of effort during the exposure to subliminal visual cues. Although the present experiments were intended to be exploratory and not designed for this purpose, some potential psychological explanations for the current findings are worthy of consideration. For instance, within the framework of the broaden and build hypothesis (Fredrickson, 2001), positive emotions have been found to broaden the scope of attention and thought-action repertoires compared to a neutral condition, whereas negative emotions narrow thought action repertoires (Fredrickson and Branigan, 2005). Broadening the scope of attention may therefore facilitate attentional dissociation, which has been found to reduce RPE (Lind et al., 2009). Similarly, broadening the scope of thought-action repertoires via the implementation of positive affect may theoretically aid in the activation of task relevant mental representations. In particular it has been proposed that the activation of these mental representations prompts the behavioral effects that occur following the exposure to non-conscious visual cues (Dijksterhuis et al., 2005). With regards to affective cues this is associated with the non-conscious activation of emotion concepts (Niedenthal et al., 2009). These emotion concepts represent an individual schema of memories, motivations and behaviors that surround a precise emotion (Lang et al., 1998). Pertinently, when emotion concepts are activated by a specific affective cue, they are proposed to elicit a behavioral response that is associated with the specific cue (Zemack-Rugar et al., 2007; Silvestrini and Gendolla, 2011b). As such, subliminal priming with visual cues related to happiness and sadness may have respectively activated the concepts of ease and difficulty that have been associated with these emotions (Silvestrini and Gendolla, 2011b; Gendolla, 2012). Similarly, Gendolla and Silvestrini (2010) have proposed that the priming of general action and inaction words can activate matching effort related mental representations. For example, these words are proposed to represent goal motivated end states such that the priming of action words activates the goal to pursue contextually relevant active behavior whereas inaction words activate the goal of inaction and thus task termination (Albarracin et al., 2011). The activation of mental representations of ease or action may therefore have facilitated the lower RPE that allowed individuals to cycle for longer before they voluntarily terminated exercise. Alternatively, activating the mental representations of difficulty or inaction may have contributed to premature task termination by surreptitiously elevating RPE.

In conjunction with the theme of non-consciously activated mental representations, it has also been reported that the sensitivity to non-conscious reward priming increases as effort becomes more pronounced (Bijleveld et al., 2012). As such it is possible that the non-conscious visual primes became more influential as the TTE test progressed and RPE correspondingly increased. Intuitively, such an effect would progressively intensify the desire for task termination when paired with sad faces or inaction words while a prolonged willingness to continue with the task would be expected at high levels of effort when paired with happy faces or action words.

In addition to the similar pre-exercise mood ratings, conscious appraisals of mood did not change from pre to post-exercise and were not different between affective priming conditions. These similarities in conscious mood ratings might initially imply that the subliminal manipulation of affect in the present study was not effective. However, the present finding is consistent with other studies that have utilized non-conscious affective priming (Winkielman and Nowak, 2005; Zemack-Rugar et al., 2007; Silvestrini and Gendolla, 2011b). In these studies it has been suggested that not only are non-conscious affective cues able to modify affective states, but that the affective state itself is also not consciously experienced. This phenomenon has again been attributed to the non-conscious activation of mental representations such that behavioral alterations that are aligned with changes in affect occur despite the inability of participants to consciously report a change in affective state (Zemack-Rugar et al., 2007). As conscious affect was not measured during the TTE test while the subliminal priming procedure took place however, this is currently a hypothetical consideration. Nonetheless, the concept that endurance performance can be altered even when a change in affective state is not consciously perceived does impart an intriguing direction for future research. Further research is also required to understand the neural mechanisms underlying the effects of non-conscious visual cues related to affect and action on perception of effort and endurance performance. Particular clarification might be gleaned from placing emphasis on the anterior cingulate cortex. This cortical area is associated with perception of effort in humans (Williamson et al., 2002) and effort-based decision-making in both non-human animals and humans (Kurnaiwan et al., 2011) and shows greater activation when humans are subliminally primed with happy faces compared to sad faces (Killgore and Yurgelun-Todd, 2004); hence providing a plausible mechanism for the link between subliminal cues and effort.

From a practical perspective, the importance of the present findings are best signified when their effects are compared to the effects of physiological factors known to alter endurance performance. For instance the 12% difference in TTE resulting from subliminal priming with happy or sad faces and the 17% difference in TTE between subliminal priming with action and inaction words can be likened to the negative effects of inspiratory muscle fatigue (14%; Wüthrich et al., 2013), and locomotor muscle fatigue (18%; Marcora et al., 2008). Placing the present findings in this context emphasizes the implications for endurance athletes who may be exposed to non-conscious visual cues during training or competition. Furthermore, because perception of effort is considered to represent one of the main barriers to exercise (Bauman et al., 2012), non-conscious visual cues related to affect and action may also effect exercise adherence in a similar manner.

Despite the theoretical and practical implications of the present experiments, it is also important to recognize some potential limitations. For instance, because a control condition was not utilized in either experiment it is not possible to establish whether the difference in TTE resulted from an increase in endurance performance following subliminal priming with happy faces or action words, a decrease in endurance performance following subliminal priming with sad faces or inaction words, or a combination of both effects. However, it was decided that establishing the existence of an overall effect of non-conscious visual cues on endurance performance was the most pertinent aim of each of these proof of principle studies. Hence, on this occasion, the use of one experimental condition and a control condition was not implemented. In addition, due to the crossover design of both investigations, a forced prime recognition check was not carried out at the culmination of each study. This was again however a known consequence of each methodological design. Specifically, while it is acknowledged that this manipulation check is important, in this instance it was reasoned that a within participant design would more effectively answer our research questions and that this approach would confound such a check. This is because implementing a forced prime recognition check only after the final subliminal priming visit may have introduced recall bias owing to the fact that participants would have been required to recall facial expressions not only for the task that they had just completed, but also for those of the previous visit(s).

In the second experiment a single subject design was implemented to exhibit the use of randomization tests as an important and effective methodological approach to single subject research. It should be noted however that randomization tests lack any ecological validity beyond that of the individual investigated. Wider generalization of the present findings is therefore not possible. Nonetheless, the strength of these tests also resides in this focused individual approach. Importantly, the repeated assessment approach that is inherent in Experiment 2 also permits some interpretation of the manner in which the priming intervention itself may have worked. For instance, the findings hint at the possibility that the effects of action and inaction word priming is acute as opposed to long lasting. As such this approach may be repeatedly used to acutely manipulate performance. It should also be noted that the TTE in Visit 2 was markedly shorter than all others. This occurred despite the participant having adhered to all their instructions prior to the visit. Although the data from this visit may be a genuine result of the treatment manipulation, and should not be regarded as otherwise, it is also acknowledged that it could be anomalous. To account for this the raw performance value for this visit was substituted with the highest TTE value of the corresponding visit within that block. Importantly, despite doing so the difference between conditions remained significant.

Notwithstanding the methodological considerations, obvious directions for future research include the addition of a control condition to the present design to help establish the directional effects of the non-conscious visual cues used in Experiments 1 and 2. Likewise, replicating Experiment 2 from a group based perspective would facilitate wider generalization regarding the effects on non-conscious action and inaction words on RPE and endurance performance. Such approaches might clarify whether non-conscious visual cues can be used as a performance-enhancing strategy during training and competitions in endurance athletes, e.g., by using contemporary technology such as smart glasses. This would also establish whether non-conscious visual cues may be an effective tool to reduce perception of effort and, thus, improve exercise adherence in recreational exercisers. In addition, it would be useful to assess whether these subliminal priming effects remain when individuals are aware that they are being subliminally primed as this would mitigate the ethical considerations associated with subliminal priming. Moreover, the investigation of pre-event subliminal priming may permit a direct approach to performance enhancement in competitive events by eliminating the necessity for visual display technology during the event itself. Finally, the impact of alternative visual cues such as anger or disgust may provide further invaluable insights into some of the factors that non-consciously influence endurance performance.

In conclusion, the collective findings of Experiments 1 and 2 are the first to show that subliminal visual cues can influence perception of effort and endurance performance. These novel findings corroborate the suggestion that endurance performance is regulated by psychobiological factors. Together, this supports and extends the explanatory power of the psychobiological model of endurance performance and the suggestion that any physiological or psychological factor affecting perception of effort and/or potential motivation will affect endurance performance (Marcora et al., 2008). Practically, the present research also has considerable implications for individuals who may be subjected to non-conscious visual cues during recreational exercise, physical training, and competitive endurance events. The fact that this finding occurred in two different experimental contexts therefore highlights the potential strength of non-conscious psychological manipulations and provides a robust platform to further investigate the role played by non-conscious visual cues during endurance performance. As such, future emphasis should be placed on non-conscious strategies designed to ensure optimal performance in endurance athletes and improve exercise adherence in the general population at both a group level and on an individually tailored basis.

AUTHORS CONTRIBUTION

Anthony Blanchfield, James Hardy, and Samuele Marcora contributed to the conception and design of the work. Acquisition was performed by Anthony Blanchfield and analysis and interpretation of the work was conducted by Anthony Blanchfield, James Hardy, and Samuele Marcora. Anthony Blanchfield, James Hardy, and Samuele Marcora were involved in all stages of the drafting and revision of the work as well as final approval of the version to be published. All authors (Anthony Blanchfield, James Hardy, and Samuele Marcora) agree to be accountable for all aspects of the work.

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Mental fatigue induced by prolonged self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise

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It has been shown that the mental fatigue induced by prolonged self-regulation increases perception of effort and reduces performance during subsequent endurance exercise. However, the physiological mechanisms underlying these negative effects of mental fatigue are unclear. The primary aim of this study was to test the hypothesis that mental fatigue exacerbates central fatigue induced by whole-body endurance exercise. Twelve subjects performed 30 min of either an incongruent Stroop task to induce a condition of mental fatigue or a congruent Stroop task (control condition) in a random and counterbalanced order. Both cognitive tasks (CTs) were followed by a whole-body endurance task (ET) consisting of 6 min of cycling exercise at 80% of peak power output measured during a preliminary incremental test. Neuromuscular function of the knee extensors was assessed before and after CT, and after ET. Rating of perceived exertion (RPE) was measured during ET. Both CTs did not induce any decrease in maximal voluntary contraction (MVC) torque ($p = 0.194$). During ET, mentally fatigued subjects reported higher RPE (mental fatigue 13.9 ± 3.0, control 13.3 ± 3.2, $p = 0.044$). ET induced a similar decrease in MVC torque (mental fatigue –17 ± 15%, control –15 ± 11%, $p = 0.001$), maximal voluntary activation level (mental fatigue –6 ± 9%, control –6 ± 7%, $p = 0.013$) and resting twitch (mental fatigue –30 ± 14%, control –32 ± 10%, $p < 0.001$) in both conditions. These findings reject our hypothesis and confirm previous findings that mental fatigue does not reduce the capacity of the central nervous system to recruit the working muscles. The negative effect of mental fatigue on perception of effort does not reflect a greater development of either central or peripheral fatigue. Consequently, mentally fatigued subjects are still able to perform maximal exercise, but they are experiencing an altered performance during submaximal exercise due to higher-than-normal perception of effort.

Keywords: muscle fatigue, mental exertion, neuromuscular fatigue, perceived exertion, perception of effort, sense of effort, Stroop task, response inhibition

INTRODUCTION

Self-regulation is the modulation of thought, affect, behavior, or attention via deliberate or automated use of cognitive control mechanisms (Karoly, 1993) such as response inhibition (Ridderinkhof et al., 2004). Although the effect size may be exaggerated because of publication bias (Carter and McCullough, 2013), several psychological studies have shown that few minutes of engagement with cognitive tasks (CTs) requiring self-regulation (e.g., incongruent Stroop task) can lead to impaired performance in subsequent tasks also requiring self-regulation, including physical tasks like sustained handgrip exercise (Hagger et al., 2010). This phenomenon is often referred to as self-regulatory or ego depletion because the prominent explanation is that self-regulation relies on a limited resource that, when depleted, leads to impaired self-regulation (Muraven and Baumeister, 2000).

In the context of whole-body exercise physiology, we and others found that prolonged (30–90 min) engagement with CTs requiring self-regulation impairs endurance performance during subsequent running or cycling exercise (Marcora et al., 2009; MacMahon et al., 2014; Pageaux et al., 2014). In this context, the prominent explanation for impaired endurance performance is that prolonged engagement with CTs requiring self-regulation induces a subjective state of mental fatigue characterized by feelings of tiredness/lack of energy at rest and/or higher-than-normal perception of effort during subsequent whole-body endurance exercise. In these studies, no negative effects of mental fatigue were found on the physiological systems (cardiorespiratory and metabolic) supporting whole-body endurance exercise. As motivation related to the endurance tasks (ETs) was also unaffected, the authors ascribed the observed impairment in endurance performance to the higher-than-normal perception of effort experienced by mentally fatigued subjects. Indeed, as stated by the psychobiological model of endurance performance (Marcora et al., 2008; Marcora and Staiano, 2010), exhaustion is not caused by muscle fatigue (i.e., by the inability to produce the force/power required by the ET despite a maximal voluntary effort), but is caused by the conscious decision to disengage from the ET. In highly motivated subjects, this effort-based decision is taken when they perceive their effort to be maximal and continuation of the ET seems impossible. During time to exhaustion tests at a fixed workload, higher-than-normal perception of effort means that mentally fatigued subjects reach their maximal perceived effort and disengage from the ET prematurely (Marcora et al., 2009; Pageaux et al., 2013). During self-paced time trials (Pageaux, 2014), the psychobiological model correctly predicts that mentally fatigued subjects consciously reduce the power output/speed in order to compensate for the higher-than-normal perception of effort and, thus, avoid premature exhaustion (Marcora, 2010a; Pageaux, 2014).

Although the psychobiological model seems to provide a valid explanation for the negative effects of mental fatigue on endurance performance, at present we cannot totally exclude the possibility that the negative effects of mental fatigue on endurance performance may be mediated, at least in part, by the central component of muscle fatigue: central fatigue [operationally defined as an exercise-induced decrease in maximal voluntary activation level (VAL); Gandevia, 2001]. This is relevant because, similarly to mental fatigue, muscle fatigue can also increase perception of effort and reduce performance during ETs (Marcora et al., 2008; de Morree and Marcora, 2013). Pageaux et al. (2013) recently assessed neuromuscular function of the knee extensors before and after a prolonged CT requiring self-regulation (90-min AX continuous performance task), and after a subsequent ET (submaximal isometric knee extensor exercise until exhaustion). The authors found that mental fatigue did not decrease VAL during maximal voluntary contraction (MVC) of the knee extensors before the ET, and that mental fatigue did not exacerbate central fatigue induced by the subsequent ET. Although these findings suggest that mental fatigue does not reduce the capacity of the central nervous system (CNS) to recruit the working muscles, it has to be noticed that neuromuscular function was not assessed for the same duration of exercise between conditions. Because mental fatigue reduced time to exhaustion, exercise duration was significantly different between conditions and it is possible that mental fatigue increased the rate of central fatigue development compared to the control condition. Furthermore, it is well-known that muscle fatigue is task specific (Bigland-Ritchie et al., 1995) and that both neural control of movement and systemic stress differ between single-joint and whole-body exercise (Sidhu et al., 2013). Of particular interest is the fact whole-body endurance exercise is known to induce homeostatic disturbances within the CNS that may influence central fatigue (for review see Nybo and Secher, 2004). It is therefore possible that mental fatigue can interact with these processes leading to greater central fatigue when neuromuscular function is measured after the same duration of whole-body endurance exercise.

The primary aim of this study was to test the hypothesis that mental fatigue induced by a prolonged CT requiring strong response inhibition (30-min incongruent Stroop task) exacerbates central fatigue during subsequent whole-body endurance exercise. As perception of effort can be increased by muscle fatigue (Marcora et al., 2008; de Morree et al., 2012; de Morree and Marcora, 2013), we examined both central fatigue and peripheral fatigue (i.e., fatigue produced by changes at or distal to the neuromuscular junction; Gandevia, 2001) before and after the incongruent Stroop task. Neuromuscular function was also examined after a whole-body ET consisting of 6 min of high-intensity cycling exercise in order to control for the confounding effects of exercise duration.

MATERIALS AND METHODS

SUBJECTS AND ETHICAL APPROVAL

Twelve physically active male adults (mean ± SD; age: 25 ± 4 years, height: 182 ± 5 cm, weight: 77 ± 11 kg) volunteered to participate in this study. None of the subjects had any known mental or somatic disorder. "Active" was defined as taking part in moderate to high intensity exercise at least twice a week for a minimum of 6 months. Our subjects can be included in the performance level 2 in the classification of subject groups in sport science research (de Pauw et al., 2013). Each subject gave written informed consent prior to the study. Experimental protocol and procedures were approved by the local Ethics Committee of the Faculty of Sport Sciences, University of Burgundy in Dijon. All subjects were given written instructions describing all procedures related to the study but were naive of its aims and hypotheses. At the end of the last visit, subjects were debriefed and asked not to discuss the real aims of the study with other participants. The study conformed to the standards set by the World Medical Association (2013).

EXPERIMENTAL PROTOCOL

Subjects visited the laboratory on three different occasions. During the first visit, a preliminary incremental test (2 min at 50 W + 50 W increments every 2 min) was performed until exhaustion (defined as a cadence below 60 RPM for more than 5 s despite strong verbal encouragement) on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands) to measure peak power output (303 ± 30 W). The cycle ergometer was set in hyperbolic mode, which allows the power output to be regulated independently of cadence over the range of 30–120 RPM. Before the incremental test the position on the cycle ergometer was adjusted for each subject, and settings were recorded and reproduced at each subsequent visit. Thirty minutes after the incremental test, subjects were familiarized with all experimental procedures.

During the second and third visit, subjects performed a 30-min CT either involving response inhibition (self-regulation task) or a control task (see *Cognitive Tasks*) in a randomized and counterbalanced order. After the CTs and a short warm up, subjects performed 6 min of high intensity cycling exercise at a fixed workload (see *Whole-Body Endurance Task*). Neuromuscular function of the knee extensors was tested before and after the CTs, and after the whole-body ET (see *Neuromuscular Function Tests*). Mood was assessed before and after the CTs, subjective workload was assessed after the CTs and after the ET. For more details see *Physiological and Psychological Measurements*. An overview of the experimental protocol performed during the second and third visit is presented in **Figure 1**. Heart rate (HR) was recorded continuously throughout the experiment. Each participant completed all three visits over a period of 2 weeks with a minimum of 48 h recovery period between visits. All participants were given instructions to sleep for at least 7 h, refrain from the consumption of alcohol, and not to practice vigorous physical activity the day before each visit. Participants were also instructed not to consume caffeine and nicotine

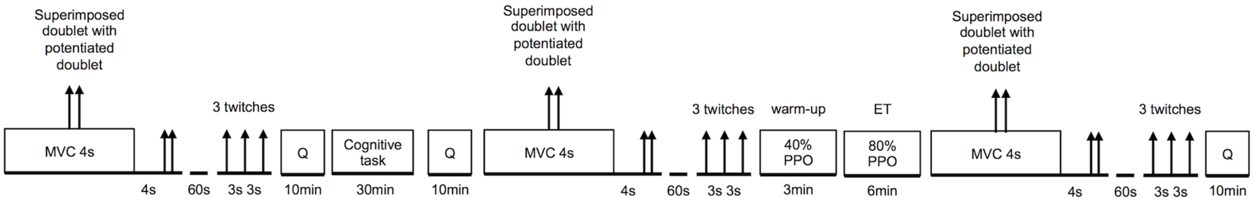

FIGURE 1 | Graphical overview of the experimental protocol. Order and timing were the same for each subject and each visit. Q, psychological questionnaires; PPO, peak power output; MVC, maximal voluntary contraction; ET, whole-body endurance task.

for at least 3 h before testing, and were asked to declare if they had taken any medication or had any acute illness, injury, or infection.

COGNITIVE TASKS

Both CTs were performed for 30 min, and they are identical to those used by Pageaux et al. (2014) to reduce self-paced endurance running performance. An incongruent Stroop task and a congruent Stroop task were used respectively for the self-regulation task and the control task (Stroop, 1992). A brief description of these CTs can be found below.

Self-regulation task

The modified incongruent Stroop task used as self-regulation task consisted of color words (yellow, blue, green, red) printed in a different ink color (either yellow, blue, green, red) presented on a computer screen. Subjects were instructed to press one of four colored buttons on the computer keyboard (yellow, blue, green, red) with the correct response being the button corresponding to the ink color (either yellow, blue, green, red) of the word presented on the computer screen. If however, the ink color was red, the button to be pressed was the button linked to the real meaning of the word, not the ink color (e.g., if the word blue appears in red, the button blue has to be pressed). If the ink color was blue, green or yellow, then the button pressed matched the ink color. The word presented and its ink color were randomly selected by the computer (100% incongruent). Subjects were instructed to respond as quickly and accurately as possible. Feedback (correct or incorrect response, reaction time, and response accuracy so far) was provided on the computer screen after each word. Participants were also informed that points would be awarded for speed and accuracy of their responses, and the score for both CTs would be added to the score for each time trial.

Control task

The congruent version of the Stroop color-word task used as control task was similar to the modified incongruent version of the Stroop color-word task. However, all words and their ink color were matched in order to greatly reduce the extent of self-regulation required by the CT. Subjects were familiarized with both CTs during the first visit to the laboratory. Response accuracy (percentage of correct responses) and reaction time were measured to monitor cognitive performance. Data were averaged every 5 min and analyzed offline using the E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA). No filters were applied to trim the reaction time data.

WHOLE-BODY ENDURANCE TASK

Fifteen minutes after completion of the CT, subjects performed the whole-body ET on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, The Netherlands) set in hyperbolic mode. After a 3-min warm-up cycling at 40% of peak power output (121 ± 12 W), subjects cycled at 80% of peak power output (242 ± 23 W) for 6 min. Cadence was freely chosen between 60 and 100 RPM, and a fan was placed in a standardized position in front of the subject during the entire duration of the task. Feedback on elapsed time, cadence, power output, and HR was not available to the subject. Once the 6 min were elapsed, subjects stopped cycling immediately and were transferred to the isokinetic dynamometer for the assessment of neuromuscular function (see *Neuromuscular Function Tests*). At the end of the warm-up, and at the end of each minute thereafter, rating of perceived exertion (RPE) and cadence were recorded. Subjects were familiarized with the whole-body ET during the first visit to the laboratory.

NEUROMUSCULAR FUNCTION TESTS

All participants were familiarized with all neuromuscular function tests during their first visit to the laboratory. The neuromuscular function tests performed in this study are identical as those performed by Pageaux et al. (2013).

Electrical stimulation

Both single and double (100 Hz frequency) stimulation were used for assessment of neuromuscular function. All central fatigue parameters were obtained within 45 s after completion of the whole-body ET. Transcutaneous electric1ally evoked contractions of the knee extensor muscles were induced by using a high-voltage (maximal voltage 400 V) constant-current stimulator (model DS7 modified, Digitimer, Hertfordshire, UK). A monopolar cathode ball electrode (0.5 cm diameter) pressed into the femoral triangle by the same experimenter during all tests was used to stimulate the femoral nerve. To ensure reliability of measurement, the site of stimulation producing the largest resting twitch amplitude and compound muscle action potential (M-wave) was marked on the skin with permanent marker. The anode was a 50 cm^2 (10 × 5 cm) rectangular electrode (Compex SA, Ecublens, Switzerland) located on the gluteus maximus opposite to the cathode. The stimulus intensity required to evoke a maximal compound muscle action potential (M_{max}) was determined at rest and during submaximal isometric knee extensors contractions (50% MVC) before the experiment on each day. The stimulus duration was 1 ms and the interval of the stimuli in the doublet was 10 ms. Supramaximal intensities ranged from 74 to 140 mA. Timing of stimulation was as follow (see **Figure 1**): (i) MVC (duration of ~4 s) with superimposed supramaximal paired stimuli (doublet) at 100 Hz and followed (4 s intervals) by paired stimuli at 100 Hz, (ii) 60 s rest and (iii) three single supramaximal stimulations at rest (interspaced by 3 s). Methodology and supramaximal intensities are according to previous studies (e.g., Place et al., 2005; Pageaux et al., 2013).

Mechanical recordings

An isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, NY, USA) was used to record the torque signal. The axis of the dynamometer was aligned with the knee axis, and the lever arm was attached to the shank with a strap. Two crossover shoulder harnesses and a belt limited extraneous movement of the upper body. Neuromuscular function tests were performed with a knee angle of 90° of flexion (0° = knee fully extended) and a hip angle of 90°. The following parameters were analyzed from the twitch response (average of 3 single stimulation interspaced by 3 s): peak twitch (Tw), time to peak twitch (contraction time, Ct), average rate of force development (RFD = Tw/Ct), and half-relaxation time. The peak torque of the doublet (potentiated doublet, 5 s after the MVC) was also analyzed. MVC torque was considered as the peak torque attained during the MVC, and guidelines to perform MVCs were respected (Gandevia, 2001). VAL during the MVC was estimated according to the following formula:

$$\mathrm{VAL} = \left(1 - \frac{\text{superimposed doublet amplitude}}{\text{potentiated doublet amplitude}}\right) \times 100$$

Because of technical issue (no potentiated doublet for one subject as the stimulator wire was damaged), VAL and doublets were analyzed only for 11 on 12 subjects. Mechanical signals were digitized on-line at a sampling frequency of 1 kHz using a computer, and stored for analysis with commercially available software (AcqKnowledge 4.1 for MP Systems, Biopac Systems Inc., Goleta, CA, USA).

Electromyographic recordings

Electromyogram (EMG) of the vastus lateralis (VL) and rectus femoris (RF) muscles was recorded with pairs of silver chloride circular (recording diameter of 10 mm) surface electrodes (Swaromed, Nessler Medizintechnik, ref 1066, Innsbruck, Austria) with an interelectrode (center-to-center) distance of 20 mm. Low resistance between the two electrodes ($<5\ \mathrm{k\Omega}$) was obtained by shaving the skin and removing the dirt from the skin using alcohol swabs. The reference electrode was attached to the patella of the right knee. Myoelectrical signals were amplified with a bandwidth frequency ranging from 10 to 500 Hz (gain = 1000 for RF and 500 for VL), digitized on-line at a sampling frequency of 2 kHz using a computer, and stored for analysis with a commercially available software (AcqKnowledge 4.1 for MP Systems, Biopac Systems Inc., Goleta, CA, USA). The root mean square (RMS), a measure of EMG amplitude, was automatically calculated with the software. Peak-to-peak amplitude of the M-waves were analyzed for VL and RF muscles with the average of the three trials used for analysis. EMG amplitude of VL and RF muscles during the MVC was quantified as the RMS for a 0.5 s interval at peak torque (250 ms interval either side of the peak torque). Maximal EMG RMS values for VL and RF muscles were then normalized by the M-wave peak-to-peak amplitude for the respective muscles, in order to obtain the RMS/M-wave ratio. This normalization procedure accounted for peripheral influences such as neuromuscular propagation failure. EMG RMS was calculated for the last 30 s of each minutes during the whole-body ET for both VL and RF. The EMG RMS during the whole-body ET was normalized to the EMG RMS of the last 30 s of the first minute of the whole-body ET.

PHYSIOLOGICAL AND PSYCHOLOGICAL MEASUREMENTS

All participants were familiarized with all psychological measurements during their first visit to the laboratory. The psychological measurements performed in this study are identical as those performed by Pageaux et al. (2014).

Heart rate

Heart rate was recorded continuously during both CTs and the whole-body ET using a HR monitor (Polar RS400, Polar Electro Oy, Kempele, Finland) with an acquisition frequency of 5 sample/s. Data were analyzed offline and averaged for both CTs. During the whole-body ET, HR data were averaged every minute.

Perception of effort

During the whole-body ET, perception of effort was measured at the end of the warm-up and every minute thereafter using the 15 points RPE scale (Borg, 1998). Standardized instructions for memory anchoring of the scale were given to each subject before the warm-up. Briefly subjects were asked to rate the conscious sensation of how hard, heavy, and strenuous the physical task was (Marcora, 2010b). For example nine corresponds to a "very light" exercise. For a normal, healthy person it is like walking slowly at his or her own pace for some minutes. Seventeen corresponds to a "very hard" and strenuous exercise. A healthy person can still go on, but he or she really has to push him or herself. It feels very heavy, and the person is very tired.

Mood

The Brunel Mood Scale (BRUMS) developed by Terry et al. (2003) was used to quantify current mood ("How do you feel right now?") before and after the CTs. This questionnaire contains 24 items (e.g., "angry, uncertain, miserable, tired, nervous, energetic") divided into six subscales: anger, confusion, depression, fatigue, tension, and vigor. The items are answered on a five points scale (0 = not at all, 1 = a little, 2 = moderately, 3 = quite a bit, 4 = extremely), and each subscales, with four relevant items, can achieve a raw score in the range of 0–16. Only scores for the Fatigue and vigor subscales were considered in this study as subjective markers of mental fatigue.

Subjective workload

The National Aeronautics and Space Administration Task Load Index (NASA-TLX; Hart and Staveland, 1988) was used to assess subjective workload. The NASA-TLX is composed of six subscales: Mental Demand (How much mental and perceptual activity was required?), Physical Demand (How much physical activity was required?), Temporal Demand (How much time pressure did you feel due to the rate or pace at which the task occurred?), Performance (How much successful do you think you were in accomplishing the goals of the task set by the experimenter?), Effort (How hard did you have to work to accomplish your level of performance?), and Frustration (How much irritating, annoying did you perceive the task?). The participants had to score each of the items on a scale divided into 20 equal intervals anchored by a bipolar descriptor (e.g., High/Low). This score was multiplied by 5, resulting in a final score between 0 and 100 for each of the six subscales. Participants completed the NASA-TLX after the CT and after the whole-body ET.

STATISTICS

All data are presented as means ± standard deviation (SD) unless stated. Assumptions of statistical tests such as normal distribution and sphericity of data were checked as appropriate. Lower-Bound correction to the degrees of freedom was applied when violations to sphericity were present. Paired *t*-tests were used to assess the effect of condition (mental fatigue vs. control) on HR during both CTs and on NASA-TLX scores after the CTs and after the whole-body ET. Fully repeated measure 2 × 6 ANOVAs were used to test the effects of condition and time on response accuracy and reaction time during the CTs. Fully repeated measure 2 × 2 ANOVAs were used to test the effects of condition and time on mood before and after the CTs. Fully repeated measure 2 × 3 ANOVAs were used to test the effects of condition and time on MVC torque, VAL, M-wave parameters for each muscle, RMS/M-wave ratio, twitch properties, and peak doublet torque before and after the CTs, and after the whole-body ET. Fully repeated measure 2 × 6 ANOVAs were used to test the effects of condition and time on HR, and EMG RMS during the whole-body ET. Fully repeated measure 2 × 7 ANOVA was used to test the effects of condition and time on RPE and cadence during the whole-body ET. Significant main effects of time and significant interactions were followed up with Bonferroni tests as appropriate. Significance was set at 0.05 (2-tailed) for all analyses, which were conducted using the Statistical Package for the Social Sciences, version 20 for Mac OS X (SPSS Inc., Chicago, IL, USA). Cohen's effects size d_z and f(V) were calculated with G*Power software (version 3.1.6, Universität Düsseldorf, Germany) and reported.

RESULTS

COGNITIVE TASKS

Mood

Self-reported fatigue was significantly higher [$p = 0.009$, $f(V) = 0.957$] post-CTs (mental fatigue condition 3.7 ± 3.4, control condition 4.5 ± 3.6) compared to pre-CTs (mental fatigue condition 1.5 ± 2.0, control condition 1.8 ± 1.5). However, neither the main effect of condition [$p = 0.369$, $f(V) = 0.951$] nor the interaction [$p = 0.401$, $f(V) = 0.264$] were significant. Vigor decreased [$p = 0.009$, $f(V) = 0.283$] significantly after the self-regulation task (10.2 ± 3.0 to 8.3 ± 3.9) and the control task (10.6 ± 4.0 to 7.8 ± 4.7) with no significant difference between conditions [interaction $p = 1.000$, $f(V) = 0.032$].

Cognitive performance

Response accuracy during CTs did not present any main effect of condition [$p = 0.070$, $f(V) = 0.605$] or time [$p = 0.236$, $f(V) = 0.378$]. Reaction time during both conditions did not change over time [$p = 0.507$, $f(V) = 0.207$] but was significantly longer during the self-regulation task compared to the control task [834 ± 109 vs. 597 ± 80 ms, $p < 0.001$, $f(V) = 2.500$]. Reaction time during the self-regulation task was significantly higher for all subjects.

Heart rate

Heart rate was significantly higher ($p < 0.001$, $d_z = 0.577$) during the self-regulation task (65.8 ± 9.3 beats/min) compared to the control task (62.0 ± 4.5 beats/min).

Subjective workload

Data on all six subscales of the NASA-TLX are presented in **Figure 2**. Following the CTs (**Figure 2A**), subjects rated higher mental demand ($p = 0.012$, $d_z = 0.861$), temporal demand ($p = 0.050$, $d_z = 0.626$) and effort ($p = 0.022$, $d_z = 0.772$) during the self-regulation task (mental fatigue condition) than during the control task (control condition). Physical demand, performance and frustration did not differ significantly between conditions.

EFFECTS OF MENTAL FATIGUE ON THE PHYSIOLOGICAL AND PSYCHOLOGICAL RESPONSES TO THE SUBSEQUENT WHOLE-BODY ENDURANCE TASK

Heart rate

Heart rate (**Figure 3A**) increased significantly over time [$p < 0.001$, $f(V) = 4.776$] but did not differ between conditions [$p = 0.381$, $f(V) = 0.274$].

Cadence and EMG amplitude

Cadence (mental fatigue condition 84.4 ± 5.4 RPM, control condition 84.2 ± 6.0 RPM) during the whole-body ET did not present any main effect of condition [$p = 0.919$, $f(V) = 0.031$], time [$p = 0.175$, $f(V) = 0.418$], or interaction [$p = 0.101$, $f(V) = 0.412$].

Electromyogram amplitude data are presented in **Figure 3**. EMG RMS of the VL muscle (**Figure 3C**) increased significantly during the whole-body ET [$p = 0.002$, $f(V) = 1.25$]. EMG RMS of the VL muscle was significantly higher during the mental fatigue condition compared to the control condition [$p = 0.046$, $f(V) = 0.678$]. EMG RMS of the RF muscle increased significantly during the whole-body ET [$p = 0.002$, $f(V) = 1.305$] without any main effect of condition [$p = 0.610$, $f(V) = 0.167$] or interaction [$p = 0.626$, $f(V) = 0.160$]. Time course of EMG RMS for the VL (**Figure 3B**) and RF (**Figure 3D**) muscles did not differ between conditions [VL, $p = 0.111$, $f(V) = 0.523$; RF, $p = 0.410$, $f(V) = 0.272$] and did not present a significant interaction [VL, $p = 0.091$, $f(V) = 0.557$; RF, $p = 0.384$, $f(V) = 0.289$].

Perception of effort

Rating of perceived exertion during the whole-body ET (**Figure 4A**) increased over time following both CTs [$p < 0.001$, $f(V) = 3.590$]. However, subjects rated a higher perceived exertion during the mental fatigue condition compared to the control condition [$p = 0.044$, $f(V) = 0.680$]. No significant interaction

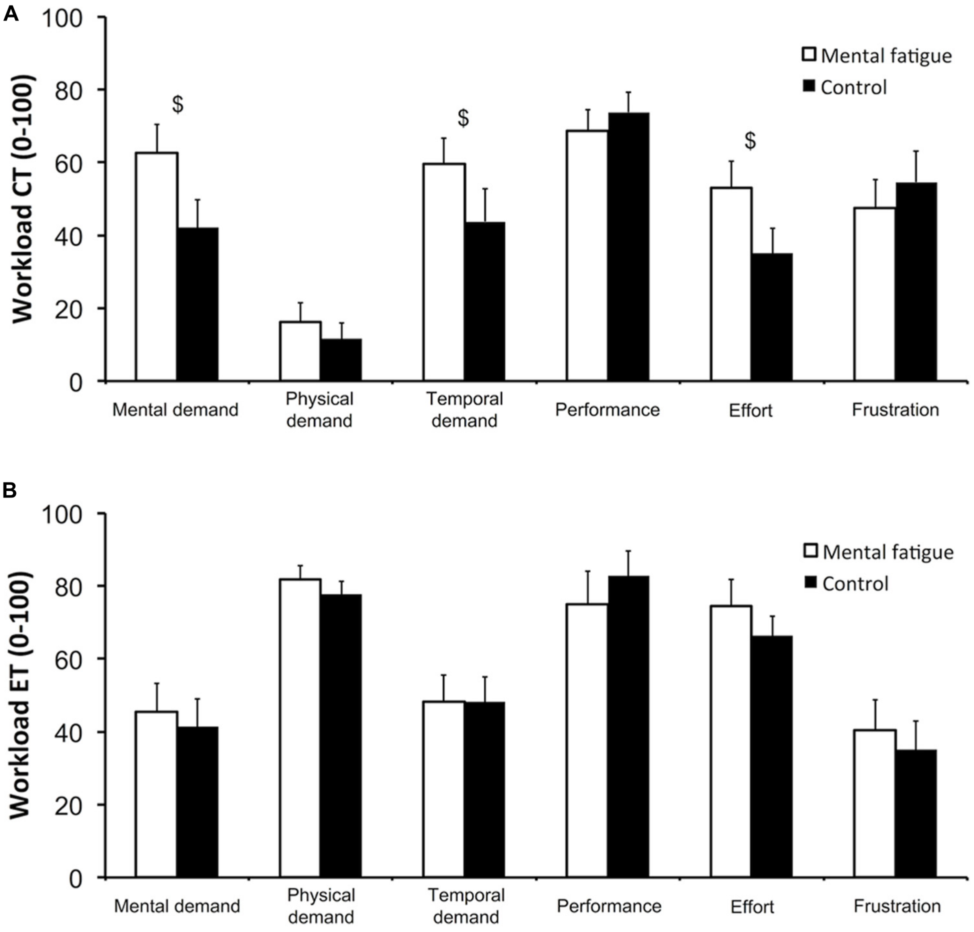

FIGURE 2 | Subjective workload of the cognitive tasks (CTs, A) and of the whole-body endurance task (ET, B). National Aeronautics and Space Administration Task Load Index (NASA-TLX) subscales. $ Significant main effect of condition ($p < 0.05$). Data are presented as mean ± SEM.

was demonstrated [$p = 0.630$, $f(V) = 0.217$]. Ratings of perceived exertion were significantly higher during the mental fatigue condition compared to the control condition for 9 out of all subjects (**Figure 4B**).

Subjective workload

Following the whole-body ET (**Figure 2B**), none of NASA-TLX subscales presented any significant difference between conditions (all $p > 0.050$).

EFFECTS OF MENTAL FATIGUE AND WHOLE-BODY ENDURANCE TASK ON NEUROMUSCULAR FUNCTION

Maximal voluntary contraction

There was no significant main effect of condition [$p = 0.920$, $f(V) = 0.032$] nor interaction [$p = 0.515$, $f(V) = 0.204$] on MVC torque of the knee extensors (**Figure 5A**). Follow-up tests on the significant main effect of time [$p = 0.001$, $f(V) = 1.319$] revealed that the CTs did not affect MVC torque [$p = 0.194$, $d_z = 0.580$]. The whole-body ET caused a significant reduction in MVC torque in both conditions (mental fatigue condition –17 ± 15%, control condition –15 ± 11%, $p = 0.001$, $d_z = 1.890$).

Peripheral fatigue

Peripheral parameters of neuromuscular function are presented in **Table 1**. There were no significant main effects of condition or interactions on all twitch parameters (all $p > 0.050$). Tw [$p < 0.001$, $f(V) = 2.610$], doublet [$p < 0.001$, $f(V) = 1.636$], Ct [$p = 0.010$, $f(V) = 0.936$], and RFD [$p = 0.003$, $f(V) = 0.938$] decreased significantly over time. The follow-up tests of the significant main effect of time are presented **Table 1**. M-wave amplitude of VL [$p = 0.338$, $f(V) = 0.303$] and RF [$p = 0.079$, $f(V) = 0.584$] muscles were not significantly affected by the CTs and the whole-body ET. M-wave amplitude of VL and RF muscles did not differ between conditions [$p = 0.958$, $f(V) = 0.032$ and $p = 0.367$, $f(V) = 0.283$] and did not show any interaction [$p = 0.620$, $f(V) = 0.153$ and $p = 0.771$, $f(V) = 0.090$].

Central fatigue

Central parameters of neuromuscular function are presented in **Figure 5**. There was no significant main effect of condition [$p = 0.869$, $f(V) = 0.054$] or interaction [$p = 0.672$, $f(V) = 0.201$] on VAL (**Figure 5B**). Follow-up tests of the significant main effect of time [$p = 0.011$, $f(V) = 0.990$] revealed an increase in VAL

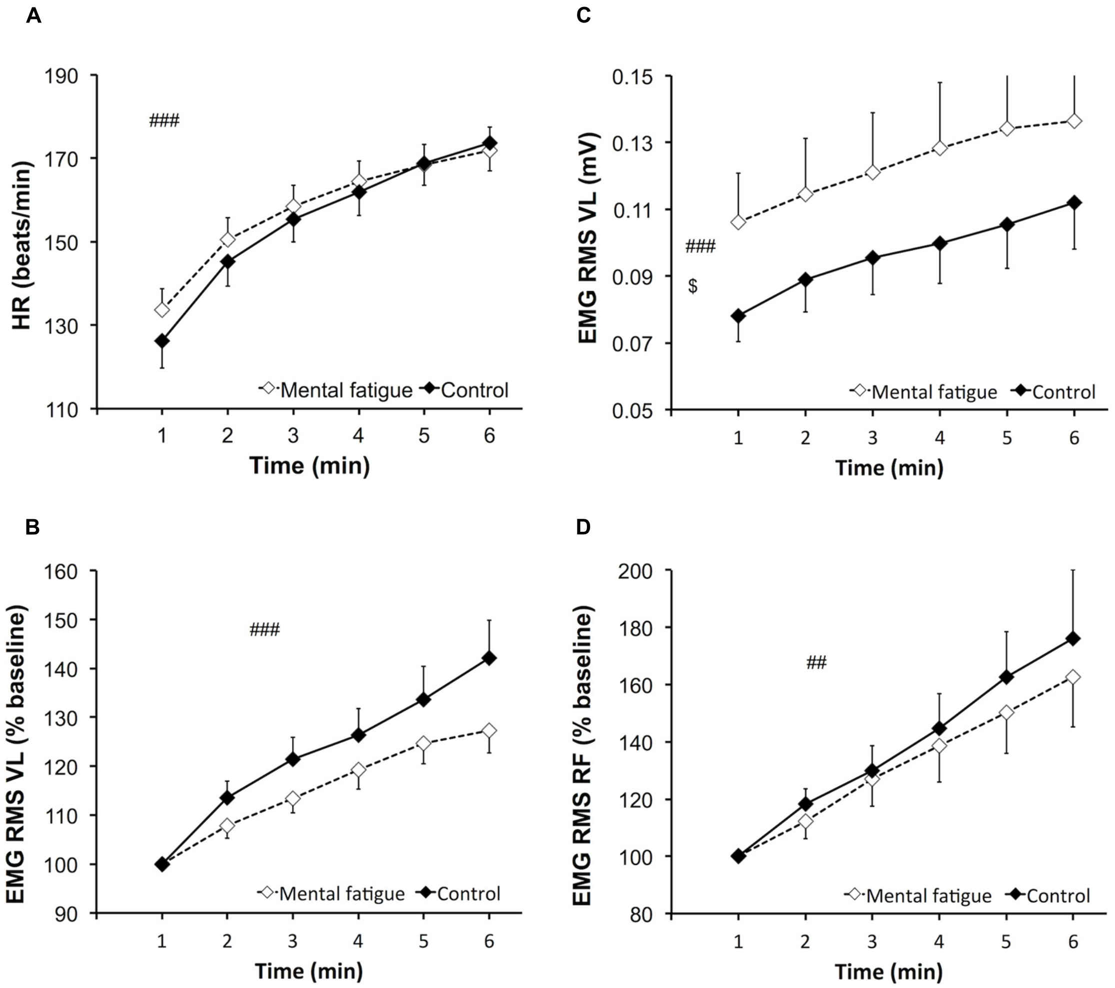

FIGURE 3 | Effects of mental fatigue on heart rate and electromyogram (EMG) amplitude of the knee extensors during the whole-body endurance task (ET). Heart rate (HR) during ET **(A)**. EMG root mean square (RMS) for the vastus lateralis (VL) muscle normalized by the first minute of ET (baseline; **B**). EMG RMS of the VL muscle during ET **(C)**. EMG RMS for the rectus femoris (RF) muscle normalized by the first minute of ET (baseline; **D**). $ Significant main effect of condition ($p < 0.05$). ## Significant main effect of time ($p < 0.01$). ### Significant main effect of time ($p < 0.001$). Data are presented as mean ± SEM.

post-CTs ($p = 0.024$, $d_z = 0.438$). On the contrary, the whole-body ET significantly reduced VAL ($p = 0.013$, $d_z = 0.880$). RMS/M-wave ratio of the VL muscle (**Figure 5C**) did not present any significant main effect of time [$p = 0.313$, $f(V) = 0.318$] or condition [$p = 0.279$, $f(V) = 0.343$]. Follow-up tests of the interaction [$p = 0.021$, $f(V) = 0.810$] revealed that the RMS/M-wave ratio of the VL muscle decreased only during the control condition following the whole-body ET ($p = 0.038$, $d_z = 0.305$). RMS/M-wave ratio of the RF muscle did not change overtime [$p = 0.063$, $f(V) = 0.280$] and did not present any main effect of condition [$p = 0.915$, $f(V) = 0.032$] or interaction [$p = 0.335$, $f(V) = 0.335$].

DISCUSSION

The primary aim of this study was to test the hypothesis that mental fatigue exacerbates central fatigue induced by whole-body endurance exercise. The results of the present study do not support this hypothesis. Furthermore, mental fatigue did not exacerbate peripheral fatigue induced by whole-body exercise. Therefore, the higher-than-normal perception of effort experienced by mentally fatigued subjects is independent of any central or peripheral alteration of neuromuscular function.

SELF-REGULATION, MENTAL FATIGUE, AND PERCEPTION OF EFFORT

We used a self-regulation task (incongruent Stroop task) to induce mental fatigue. The higher HR experienced during the incongruent Stroop task confirms that self-regulation is cognitively demanding and requires higher effort mobilization compared to the control task (Richter et al., 2008). The more demanding nature of the self-regulation task is also supported by higher ratings of mental demand, temporal demand, and effort compared to the control task. Moreover, the subjects presented a longer reaction time during the self-regulation task compared to the control task, confirming the presence of an additional cognitive control mechanism during the self-regulation task. As both control and

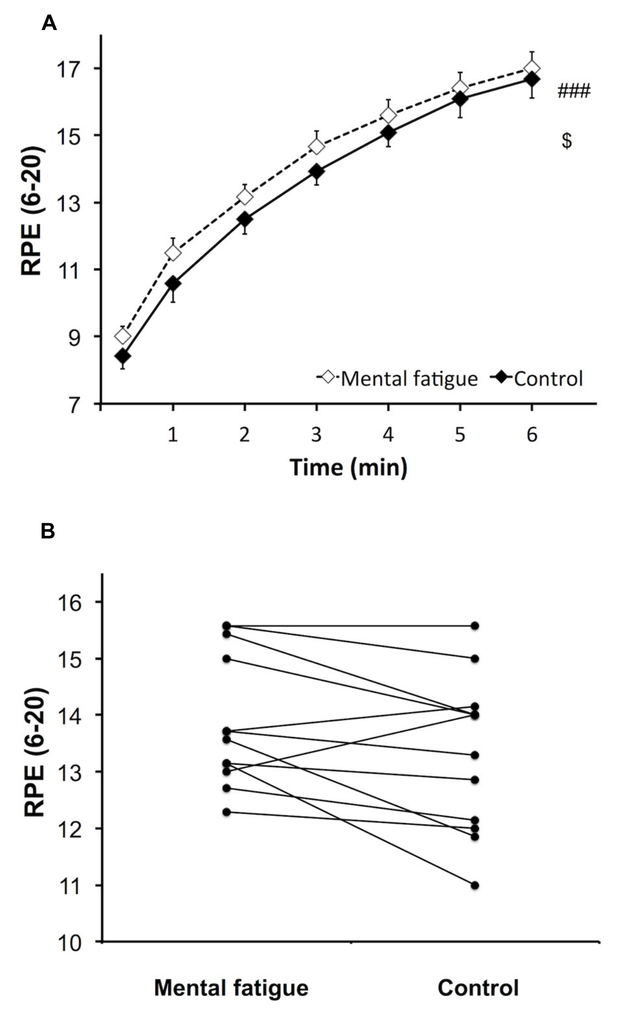

FIGURE 4 | Effects of mental fatigue on perception of effort during the whole-body ET. Overall rating of perceived exertion (RPE) during ET **(A)**. Individual effects of condition on the mean overall RPE during ET **(B)**. ### Significant main effect of time ($p < 0.001$). $ Significant main effect of condition ($p < 0.05$). Data are presented as mean ± SEM.

self-regulation tasks involved sustained attention, the longer reaction time is likely to be due to the presence of response inhibition during the self-regulation task (Stroop, 1992; Sugg and McDonald, 1994).

Interestingly, both self-regulation and control tasks induced an increase in self-reported fatigue and a decrease in vigor suggesting presence of mental fatigue following both CTs. As in a previous study (Pageaux et al., 2014) a higher level of mental fatigue in the self-regulation condition was more clearly identified by higher RPE during the subsequent whole-body ET. However, it has to be noticed that perception of effort did not increase in the self-regulatory condition in three out of 12 subjects. This may be due to the fact that the self-regulation task was performed for only 30 min, and that this duration might be insufficient to induce mental fatigue in some subjects. Random day-to-day variability in perception of effort may also mask the effect of the self-regulation task at an individual level.

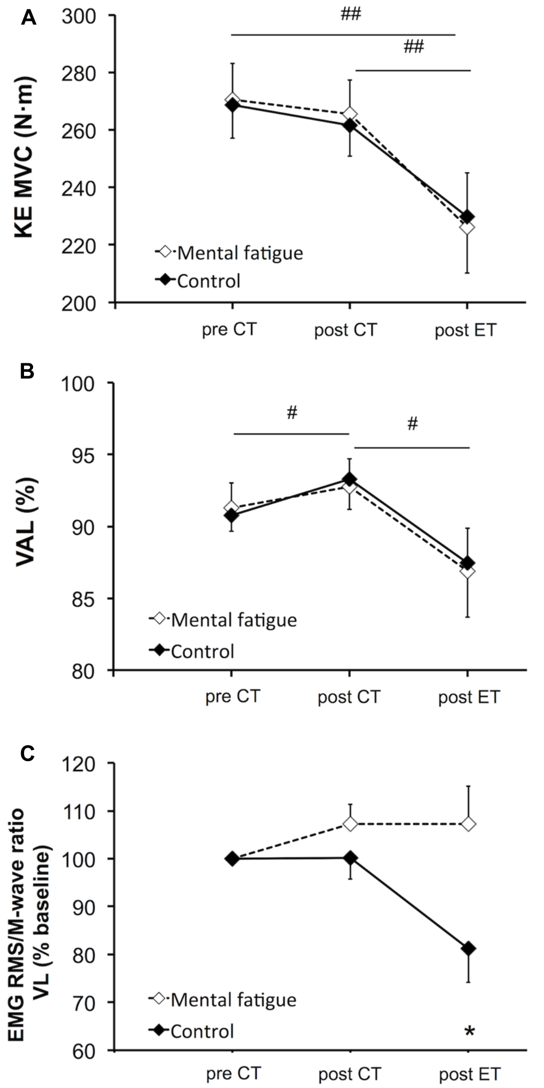

FIGURE 5 | Effects of mental fatigue on maximal voluntary contraction (MVC) of the knee extensors and central parameters of neuromuscular function. MVC torque of the knee extensors (KE, **A**). Maximal voluntary activation level (VAL, **B**). RMS/Mmax (M-wave) ratio of the VL muscle **(C)**. CT, cognitive tasks; ET, whole-body endurance task; baseline, pre CT. # Significant main effect of time ($p < 0.05$). ## Significant main effect of time ($p < 0.01$). * Significant difference between conditions for the same time ($p < 0.05$). Data are presented as mean ± SEM.

MENTAL FATIGUE DOES NOT IMPAIR NEUROMUSCULAR FUNCTION

To check that mental fatigue did not alter neuromuscular function at the onset of the whole-body ET, we performed neuromuscular function tests before and after the CTs. According to previous studies, completion of short (Bray et al., 2008) or prolonged (Pageaux et al., 2013) CTs requiring self-regulation does not alter MVC of the handgrip and knee extensor muscles. Furthermore, another previous study (Rozand et al., 2014a) found that 80 intermittent maximal imagined contractions of the elbow flexor muscles did not alter MVC despite presence of mental fatigue. Our results are in line with these findings. Indeed, in

Table 1 | Effects of mental fatigue on peripheral parameters of neuromuscular function.

	Mental fatigue			Control		
	Pre CT	**Post CT**	**Post ET**	**Pre CT**	**Post CT**	**Post ET**
M-wave amplitude VL (mV)	17.77 ± 4.06	17.41 ± 3.99	18.35 ± 5.28	17.85 ± 3.85	17.69 ± 3.24	17.83 ± 3.97
M-wave amplitude RF (mV)	9.61 ± 2.59	9.17 ± 2.32	8.67 ± 2.49	9.13 ± 2.41	8.59 ± 2.10	8.37 ± 2.36
Tw (N.m)	60 ± 14	58 ± 15$^{££}$	40 ± 12$^{£££§§§}$	56 ± 15	54 ± 12$^{££}$	36 ± 11$^{£££§§§}$
Ct (ms)	76 ± 14	76 ± 10	67 ± 10§	79 ± 10	80 ± 1.09	69 ± 11§
RFD (N.m/s)	817 ± 243	780 ± 244	610 ± 219$^{££§}$	727 ± 244	686 ± 192	526 ± 143$^{££§}$
HRT (ms)	79 ± 27	83 ± 26	75 ± 27	78 ± 27	77 ± 29	72 ± 27
Doublet (N.m)	108 ± 16	105 ± 17$^{£}$	87 ± 18$^{£££§§}$	104 ± 19	95 ± 19$^{£}$	83 ± 15$^{£££§§}$

Ct, contraction time of the twitch; Tw, peak twitch; RFD, average rate of force development the twitch; HRT, half relaxation time of the twitch; CT, cognitive task; ET, whole-body endurance task; VL, vastus lateralis muscle; RF, rectus femoris muscle. $^{£}$ *Main effect of time, significantly different from pre CT;* § *Main effect of time, significantly different from post CT. One item corresponds to* $p < 0.05$*, two items correspond to* $p < 0.01$*, and three items corresponds to* $p < 0.001$*. Data are presented as mean ± SD.*

our study, none of the CTs induced a significant decrease in knee extensors MVC.

Interestingly, as previously observed (Bishop, 2003), the absence of warm-up after the CTs impaired some peripheral parameters of neuromuscular function despite no reduction in knee extensors MVC. The absence of MVC torque reduction despite impaired muscle contractile properties can be explained by the slight increase in maximal voluntary activation of the knee extensor muscles measured post-CTs in both conditions. Indeed, an increase in VAL measured by the twitch-interpolated technique is likely to reflect an increase in muscle recruitment (Gandevia et al., 2013). Therefore, it is likely that our subjects compensated the absence of warm-up by slightly increasing muscle fibers recruitment and, thus, producing the same knee extensors MVC as prior to the CTs.

It has been suggested that CTs requiring self-regulation may cause the depletion of CNS resources, leading to reduced capacity of the CNS to recruit the working muscles (Bray et al., 2008, 2012). As both CTs did not induce a decrease in maximal muscle activation, our results and those of previous studies (Bray et al., 2008; Pageaux et al., 2013) do not support this hypothesis. However, because our study did not involve repeated MVCs, further studies are required to investigate the effect of mental exertion on the CNS capacity to recruit the working muscles during repeated contractions. The existing literature is not clear in this respect as both reduced MVC force (Bray et al., 2012) and no reductions in MVC torque and VAL (Rozand et al., 2014b) have been reported in experiments combining self-regulation tasks with repeated MVCs.

MENTAL FATIGUE DOES NOT EXACERBATE CENTRAL FATIGUE INDUCED BY WHOLE-BODY ENDURANCE EXERCISE

Muscle fatigue can be caused by peripheral and/or central alterations (for review see Gandevia, 2001). As expected, mental fatigue did not exacerbate peripheral fatigue induced by the whole-body ET. The main aim of this study was to investigate whether mental fatigue exacerbates central fatigue induced by whole-body endurance exercise. Contrary to our hypothesis, the reduction in VAL induced by the whole-body ET did not differ between conditions. These results demonstrate for the first time that prolonged engagement with a CT requiring self-regulation does not exacerbate central fatigue during subsequent whole-body endurance exercise. The present findings are similar to those of our previous study showing that mental fatigue does not exacerbate central fatigue induced by submaximal single-joint exercise when measured at exhaustion (Pageaux et al., 2013). Therefore, the present study provides further evidence that the negative effect of mental fatigue on whole-body endurance performance (Marcora et al., 2009; MacMahon et al., 2014; Pageaux et al., 2014) is not mediated by central fatigue.

As mental fatigue does not affect the capacity of the CNS to recruit the working muscles (Pageaux et al., 2013; Rozand et al., 2014b), it is now clear that mental fatigue and central fatigue are two distinct phenomena. The most plausible explanation for the lack of interaction between mental fatigue and central fatigue is that these CNS functions involve different brain areas (Pageaux et al., 2013). Indeed, functional magnetic resonance imaging studies showed that central fatigue during index finger abduction exercise is associated with decrease in activation of the supplementary motor area and to a lesser extent, in parts of the paracentral gyrus, right putamen and in a small cluster of the left parietal operculum (van Duinen et al., 2007). Interestingly, none of these brain areas is significantly associated with CTs involving response inhibition. This cognitive control mechanism is significantly associated with activity of the pre-supplementary motor area and the anterior cingulate cortex (ACC; Mostofsky and Simmonds, 2008).

MENTAL FATIGUE AND PHYSIOLOGICAL RESPONSES TO THE WHOLE-BODY ENDURANCE TASK

It has been shown previously that mental fatigue does not alter the cardiovascular, respiratory and metabolic responses to whole-body endurance exercise (Marcora et al., 2009). Our finding that the HR response to whole-body endurance exercise did not differ between conditions confirms this. Interestingly, however, the EMG RMS of the VL muscle during the whole-body ET was significantly higher following the self-regulation task compared to the control task. As cadence did not differ between conditions, this result suggests that prolonged self-regulation induced alterations in muscle recruitment at the onset and throughout the subsequent whole-body ET. This is not the first report of higher EMG amplitude during a physical task following a self-regulation task. In accordance with our results, Bray et al. (2008) measured higher EMG amplitude during sustained handgrip exercise following a short (3 min 40 s) engagement with the same incongruent Stroop task used in the present study. Therefore, our results, combined with those of Bray et al. (2008), suggest that both prolonged and short engagement with CTs requiring self-regulation can alter muscle recruitment during a subsequent physical task.

Because central and peripheral fatigue did not differ between conditions, higher EMG RMS of the VL muscle during the whole-body ET in the self-regulation condition cannot represent a compensatory increase in muscle recruitment. A possible explanation is that this EMG alteration represents an alteration in motor control in conditions of mental fatigue. This conclusion is supported by the findings of two recent studies showing that mental fatigue reduces mechanically induced tremor (Budini et al., 2014) and has adverse effects in all the three phases of slips (Lew and Qu, 2014). As injury in sport is more likely to occur in the late stage of an event or a season (e.g., Ekstrand et al., 2011), it seems that the effects of mental fatigue on motor control during whole-body physical tasks warrant further investigations.

MENTAL FATIGUE AND PERCEPTION OF EFFORT

The higher-than normal perception of effort experienced by mentally fatigued subjects in the present experiment is similar to that reported in previous studies involving submaximal single-joint exercise (Pageaux et al., 2013) and whole-body endurance exercise (Marcora et al., 2009) at a fixed workload, as well as self-paced whole-body endurance exercise (Brownsberger et al., 2013; MacMahon et al., 2014; Pageaux et al., 2014). In some of these studies, the abnormal perception of effort has been associated with the negative effect of mental fatigue on endurance performance. However, despite strong evidences that mental fatigue increases RPE and impairs performance during endurance exercise, the underlying mechanisms of this alteration in perception of effort remain unclear.

It is well-accepted that, like any other perceptions, perception of effort results from the neurocognitive processing of sensory signals. However, the nature of the sensory signals involved in perception of effort generation remains debated. Briefly, two different theoretical models suggest that perception of effort reflects the neurocognitive processing of (i) signals from premotor/motor to sensory areas of the cortex during voluntary muscle contractions (corollary discharge model; Marcora, 2009; de Morree et al., 2012, 2014); or (ii) afferent sensory signals about the physiological condition of the body (interoception) and the environment (afferent feedback model; Hampson et al., 2001). Interestingly, in our study, mentally fatigued subjects experienced a higher-than-normal perception of effort despite no significant effects of mental fatigue on HR and peripheral fatigue. Because sensory signals from the heart and peripheral muscles are considered primary sources of afferent feedback for the generation of perception of effort (Hampson et al., 2001), it is unlikely that the higher RPE observed in our study reflects an alteration of afferent feedback induced by mental fatigue. Another possibility is that the higher than-normal perception of effort observed in mentally fatigued subjects reflects higher activity of premotor and/or motor areas of the cortex (i.e., higher central motor command) during whole-body endurance exercise. Although no direct neurophysiological measures of central motor command were taken in the present study, the abnormal EMG RMS of the VL muscle during the whole-body ET suggests that alterations in motor control may force mentally fatigued subjects to increase their central motor command in order to produce the same power output even when central and peripheral fatigue are not exacerbated. Finally, preliminary evidence that prolonged and demanding cognitive activity disrupts sensorimotor gating (van der Linden et al., 2006) suggests that mental fatigue may also affect the neurocognitive processing of the sensory signals underlying perception of effort. Further studies are required to investigate whether mental fatigue (i) alters the neurocognitive processing of the corollary discharges associated with central motor command, (ii) alters the central motor command itself, or (iii) alters the neurocognitive processing of afferent sensory signals.

Despite that we did not measure intrinsic changes in the brain induced by prolonged self-regulation leading to mental fatigue, it is possible to speculate on the mechanisms involved based on previous studies. The ACC is strongly activated during incongruent Stroop tasks (Bush et al., 1998; Swick and Jovanovic, 2002) and is also known to be linked with perception of effort (Williamson et al., 2001, 2002) and effort-based decision-making (Walton et al., 2006). Furthermore, studies with caffeine suggest an association between brain adenosine and mental fatigue (Lorist and Tops, 2003). It is therefore plausible that the higher perception of effort experienced by mentally fatigued subjects is caused by an accumulation of adenosine in the ACC. Indeed, experimental evidences that neural activity increases extracellular concentration of adenosine (Lovatt et al., 2012) and that brain adenosine accumulation reduces endurance performance (Davis et al., 2003) support this hypothesis. Further studies are required to confirm these speculations, and to investigate other cortical areas and neurotransmitters involved in the negative effects of mental fatigue on perception of effort and endurance performance.

CONCLUSION

This study was the first to test the hypothesis that mental fatigue and central fatigue induced by whole-body exercise are causally related. Contrary to this hypothesis, our findings show that mental fatigue does not exacerbate central fatigue during subsequent whole-body exercise. However, we must acknowledge some limitations. Firstly, the whole-body ET had to be performed on a cycle ergometer, inducing a time delay between the end of exercise and the start of neuromuscular testing due to the need to transfer the participant from the cycle ergometer to the isokinetic dynamometer. Therefore, the extent of muscle fatigue is likely to be underestimated in both experimental conditions. Secondly, the whole-body ET consisted of 6 min of high-intensity cycling exercise at a fixed workload. Future studies should investigate the effects of mental fatigue on more prolonged low-to-moderate intensity whole-body endurance exercise including running where the extent of central fatigue may be greater (Millet and Lepers, 2004). The effects of mental fatigue on central fatigue induced by self-paced whole-body endurance exercise and repeated sprints also warrant further investigations given their relevance to both endurance competitions and team sports. Finally, brain activity during exercise was not measured in the present study and we can only speculate, based on previous studies, on the mechanisms underlying the increase in RPE observed in mentally fatigued subjects.

Despite these limitations, this study provides further evidences that mental fatigue does not reduce the capacity of the CNS to recruit the working muscles. Our results suggest that the negative effect of mental fatigue on perception of effort does not reflect a greater development of either central or peripheral fatigue. Consequently, mentally fatigued subjects are still able to perform maximal exercise, but they are experiencing an altered performance during submaximal exercise due to higher-than-normal perception of effort. Therefore, further studies should investigate the brain alterations underlying the negative effect of mental fatigue on perception of effort and endurance performance. A better understanding of these brain alterations could lead to development of novel targeted interventions to decrease perception of effort and improve endurance performance in athletes, and reduced exertional fatigue in patients (Macdonald et al., 2012).

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