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The differential effects of prolonged exercise upon executive function and cerebral oxygenation

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ABSTRACT

The acute-exercise effects upon cognitive functions are varied and dependent upon exercise duration and intensity, and the type of cognitive tasks assessed. The hypofrontality hypothesis assumes that prolonged exercise, at physiologically challenging intensities, is detrimental to executive functions due to cerebral perturbations (indicated by reduced prefrontal activity). The present study aimed to test this hypothesis by measuring oxygenation in prefrontal and motor regions using near-infrared spectroscopy during two executive tasks (flanker task and 2-back task) performed while cycling for 60 min at a very low intensity and an intensity above the ventilatory threshold. Findings revealed that, compared to very low intensity, physiologically challenging exercise (i) shortened reaction time in the flanker task, (ii) impaired performance in the 2-back task, and (iii) initially increased oxygenation in prefrontal, but not motor regions, which then became stable in both regions over time. Therefore, during prolonged exercise, not only is the intensity of exercise assessed important, but also the nature of the cognitive processes involved in the task. In contrast to the hypofrontality hypothesis, no inverse pattern of oxygenation between prefrontal and motor regions was observed, and prefrontal oxygenation was maintained over time. The present results go against the hypofrontality hypothesis.

1. Introduction

The acute-effects of physical exercise upon cognitive function have been subject to several integrative reviews and meta-analyses (Brisswalter, Collardeau, & Arcelin, 2002; Lambourne & Tomporowski, 2010; McMorris & Graydon, 2000; Tomporowski, 2003), and several moderators such as the duration and intensity of exercise and an individual's fitness level have been identified. In addition, it has been clearly described how physiological states such as metabolic depletion, dehydration, heat stress and fatigue elicit differential effects upon cognitive functions (Brisswalter et al., 2002). Dietrich and Audiffren (2011) reported how the effects of acute exercise also vary by the type of cognitive functions assessed and recommended distinguishing higher-order executive functions from underlying automatic functions (such as processing speed). In line with this recommendation, the evidence has been revisited (Chang, Labban, Gapin, & Etnier, 2012; Guiney & Machado, 2013; McMorris & Graydon, 2000). Chang et al. (2012) showed that the effects of exercise upon tasks categorized as measures of executive function were positive and significantly larger than any other category of cognitive tasks. McMorris, Sproule, Turner, and Hale (2011) focused specifically on executive functions and reported moderate to large positive effects of exercise upon central executive tasks. Executive functions include inhibitory control, working memory, and cognitive flexibility (see Diamond, 2013). These abilities are often grouped together as they all serve goal-directed behaviours and rely on the same fronto–cingulo–parietal network (Niendam et al., 2012), but they clearly provide separable functional outcomes (Miyake et al., 2000). Despite the positive effects shown by Chang et al. (2012) and McMorris et al. (2011), recent studies have shown differential effects of exercise upon inhibitory control and working memory (Drollette, Shishido, Pontifex, & Hillman, 2012; Soga, Shishido, & Nagatomi, 2015). Therefore, it seems that the positive effects of exercise upon separate executive abilities cannot be generalised.

To explain the negative effects of exercise upon executive functions, Dietrich and Audiffren (2011) proposed that executive processes would be impeded during prolonged exercise at

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physiologically challenging intensities leading to exhaustion, whereby there is an altered balance between a change in cerebral blood flow and metabolism (Dalsgaard, 2006). According to the hypofrontality hypothesis (Dietrich, 2003), the detrimental effect upon executive functions is supposed to be mediated by a reduction of activity in the prefrontal cortex, in favour of brain regions associated with sensory and motor processes. Studies that have tested tenets that align with the hypofrontality hypothesis have shown mixed results, indicating either negative (Del Giorno, Hall, O'Leary, Bixby, & Miller, 2010) or positive effects (Davranche, Brisswalter, & Radel, 2015; Lucas et al., 2012) of exercise upon executive functions. Schmit et al. (2015) initially showed positive effects on inhibitory control and no hypofrontality response (as oxygenation declined but remained above the baseline) in prefrontal regions just before exhaustion during exercise at 85% maximal aerobic capacity. However, this study did not (i) examine more than one type of executive function, (ii) compare prefrontal relative to other regions of the brain associated with motor processes, and (iii) employ exercise over a prolonged duration. Therefore, the aim of this study was to disentangle the differential effects of exercise upon higher order cognitive functions by examining two types of executive processes and regions of the brain associated with executive versus motor processes during prolonged exercise, in a test of the hypofrontality hypothesis.

Executive performance using the Eriksen flanker task (indexing inhibitory control; Machado, Wyatt, Devine, & Knight, 2007) and the 2-back task (reflecting working memory efficiency) was examined during 60 min steady state exercise at intensities above and below the ventilatory threshold. The ventilatory threshold defines the point at which a physiological steady state is difficult to maintain and corresponds to exercise in the heavy intensity domain (Gaesser & Poole, 1996). Below the ventilatory threshold, very low intensity exercise was chosen to match the biomechanical and situational aspects of the heavy intensity condition, with minimal induction of aerobic and physiological effects. The cerebral haemodynamic response was monitored while performing the executive tasks during exercise using near-infrared spectroscopy (NIRS, see Perrey, 2008). A multi-channel system was used to track changes (Δ) in oxygenation (oxy-haemoglobin [O_2Hb] concentration, a reliable index of cortical activity, see Attwell & Iadecola, 2002; Strangman, Culver, Thompson, & Boas, 2002) over the right lateral prefrontal and motor regions. The right lateral prefrontal region was chosen due to its involvement in both inhibitory control (Aron, Robbins, & Poldrack, 2004; Aron, Robbins, & Poldrack, 2014) and working memory systems (Müller, Machado, & Knight 2002; Owen, McMillan, Laird, & Bullmore, 2005), consequently the ipsilateral motor cortex was chosen.

We had two hypotheses based upon conflicting lines of evidence. On one hand, due to accumulated evidence from separate meta-analyses (Chang et al., 2012; McMorris et al., 2011) we expected that exercise would improve executive performance, which would coincide with a larger increase of prefrontal O_2Hb (Rooks, Thom, McCully, & Dishman, 2010) over time in the heavy than in the very low intensity exercise condition. On the other hand, in line with the hypofrontality hypothesis (Dietrich, 2003; Dietrich & Audiffren, 2011) we expected that exercise would impair executive performance, which would coincide with a decrease of prefrontal O_2Hb and stable (or even increased) motor O_2Hb over time in the heavy than in the very low intensity exercise condition. In either case, we expected that executive performance would mirror prefrontal O_2Hb over time. Moreover, as executive functions are separable and cannot be generalised (Miyake et al., 2000), we expected to observe task-related differences between inhibitory control and working memory processes reflected by prefrontal O_2Hb.

2. Methods

2.1. Participants

Fourteen participants (men = 9) were recruited from a student population. Participants reported partaking an average of 5.1 (±3.6) hours of physical activity per week. Due to the physiologically challenging intensity and duration of exercise, active participants were recruited so that they would be able to maintain the required intensity for the full 60 min. The volunteers signed an informed consent form approved by the University Ethics Committee prior to participation and received course credits upon completion of the study. The study was conducted in accordance with the Declaration of Helsinki. Participants' anthropometric and physiological characteristics are presented in Table 1.

2.2. Procedure

This study employed a cross over design and required the participants to visit the laboratory on three occasions (one training and two experimental sessions) at least 48 h apart and around the same time of day. In the training session, participants provided their informed consent and initial assessments (age, height and body mass) were recorded. Participants were seated on an upright cycle ergometer (Wattbike, Wattbike Ltd, Nottingham, UK), previously validated for power output ranging from 50 to 300 watts (W) at a cadence of 70–90 repetitions per minute (rpm) (Hopker, Coleman, Passfield, & Wiles, 2010), and fitted with a facemask to measure metabolic data (Fitmate Pro, COSMED, Miami, USA) and a heart rate monitor. Participants completed an incremental cycling exercise test to exhaustion with an increase of 15 to 25 W per minute and a cycling cadence ranging from 70 to 90 rpm in line with the American College of Sports Medicine (2009). The end of the test was determined by volitional cessation of exercise or failure to maintain pedal cadence above 60 rpm despite strong verbal encouragement. Maximal oxygen uptake (VO_2max) was determined by the highest 30 s average of oxygen uptake (VO_2, measured in ml kg^{-1} min^{-1}). The ventilatory threshold was identified by agreement of the point at which a disproportionate increase in VO_2 occurred between two plots, (i) VO_2 and (ii) ventilatory equivalent, over time (Gaskill et al., 2001). Participants completed a minimum of four sets (100 trials) each of the flanker and the 2-back tasks for familiarization. In order to minimise potential learning effects, additional sets of the tasks were completed until there was a <5% increase in performance from the previous set.

The order of the experimental sessions (heavy or very low intensity) and presentation of the tasks (flanker, 2-back or 2-back, flanker) was counterbalanced and participants were alternately assigned an order upon enrolment in the study. In the experimental sessions, the heart rate chest strap was fitted, the NIRS cap was carefully positioned and blood lactate was measured. The participants were seated comfortably on a cycle ergometer

Table 1
Participants' anthropometric and physiological characteristics.

Variables	M ± SD (range)
Age (years)	22.7 ± 3.8 (19–34)
Height (cm)	173.7 ± 9.1 (155–184)
Body mass (kg)	68.1 ± 12.9 (52–103)
VO_2 at VT (ml kg^{-1} min^{-1})	29.3 ± 7.3 (22.6–49.2)
VO_2 max (ml kg^{-1} min^{-1})	46.7 ± 11.2 (32–71.8)
Heart rate max (bpm)	193 ± 7 (180–203)

Notes: VO_2 = oxygen uptake; VT = ventilatory threshold; VO_2max = maximal oxygen uptake.