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Executive-related oculomotor control is improved following a 10-min single-bout of aerobic exercise: Evidence from the antisaccade task

Ashna Samani, Matthew Heath*

School of Kinesiology and Graduate Program in Neuroscience, The University of Western Ontario, London, Ontario, Canada N6A 3K7

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ABSTRACT

Previous work has shown that a single-bout of moderate-to-vigorous intensity exercise improves task-specific activity within frontoparietal networks and produces a short-term 'boost' to executive-related cognitive control – an effect in healthy young adults that is reported to be selective to exercise durations of 20 min or greater. The present study sought to determine whether such a 'boost' extends to an exercise duration as brief as 10 min. Healthy young adults performed a 10-min single-bout of moderate-to-vigorous intensity aerobic exercise (i.e., via a cycle ergometer) and pre- and post-exercise executive control was examined via the antisaccade task. Antisaccades are an executive task requiring a goal-directed eye movement (i.e., a saccade) mirror-symmetrical to a visual stimulus. The hands- and language-free nature of antisaccades coupled with the temporal precision of eye-tracking technology make it an ideal tool for identifying executive performance changes. Moreover, an extensive literature has shown that antisaccades are mediated via frontoparietal networks that are modulated following single-bout and chronic exercise training. Results showed that antisaccade reaction time (RT) reliably decreased by 27 ms from pre- to post-exercise assessments. Further, the percentage of antisaccade directional errors did not reliably vary from the pre- (13%) to post-exercise (9%) assessments – a result indicating that the RT improvement was unrelated to a speed-accuracy trade-off. A follow-up experiment involving antisaccade sessions separated by a non-exercise interval did not show a similar RT modulation. Thus, a 10-min bout of moderate-to-vigorous intensity aerobic exercise benefits executive-related oculomotor control, and is a finding we attribute to an exercise-based increase in attention/arousal and/or improved task-specific activity within the frontoparietal networks supporting antisaccades.

1. Introduction

A wealth of evidence has shown that participation in a long-term (i.e., > 6 weeks) aerobic- and/or resistance-based exercise program improves not only general physical health, but also benefits brain health (e.g., Etnier et al., 2006). Colcombe and Kramer's (2003) seminal meta-analysis reported that exercise training in healthy young and older (i.e., > 55 years of age) adults produces broad benefits in cognition (e.g., working memory and attention), and more specifically enhances executive-related control. As well, recent work by our group has shown that a 6-month aerobic and/or resistance-based exercise programs improves executive control in older adults in the prodromal stages of Alzheimer's disease (Heath et al., 2016b, 2017). Broadly speaking, executive control relates to an individual's ability to process and attend single and multiple stimuli, update and monitor working memory, and assert high-level inhibitory control (Norman and Shallice, 1986). It is thought that long-term exercise programs improve cognition and executive functioning via a range of neurophysiological changes including: (1) increased levels of brain-derived neurotrophic factors (BDNF) that promote neuroplasticity and synaptic efficiency (Cotman and Berchtold, 2002), (2) stimulating hippocampal neurogenesis via cell proliferation (van Praag et al., 1999), and (3) promoting activity, connectivity and density within frontoparietal executive structures (Colcombe et al., 2004, 2006; Ruscheweyh et al., 2011; Voss et al., 2010).

In addition to long-term exercise effects, work has examined whether a single-bout of exercise elicits a short-term cognitive 'boost'. Some work has shown that a single-bout of exercise produces a cognitive benefit (e.g., Fleury and Bard, 1987), whereas other studies have not (e.g., Coles and Tomporowski, 2008). Although the results of individual studies are mixed, Chang et al.'s (2012) meta-analysis concluded that a single-bout of exercise (aerobic, resistance, or combined) produces a small but reliable cognitive benefit when the exercise session is performed at a moderate-to-vigorous level of intensity (i.e., 60–85% of predicted maximum heart rate; see also Lambourne and Tomporowski, 2010). Moreover, Chang et al. identified that an additional moderator

* Corresponding author.
E-mail address: mheath2@uwo.ca (M. Heath).

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of the single-bout exercise effect was the administration of a task sensitive to addressing executive-related cognitive processes. Indeed, most early studies examining the single-bout effect employed tasks involving simple reaction time (RT) (Aks, 1998; Fleury and Bard, 1987; McMorris and Keen, 1994), visual recognition (Bard and Fleury, 1978), and working memory (Coles and Tomporowski, 2008), and did not report a reliable cognitive benefit. In turn, more recent work has reported that tasks involving high-level executive functioning elicit a positive exercise benefit (for review see Lambourne and Tomporowski, 2010). For example, Chang et al. (2014) had adult participants (mean age = 58.1 years) perform a single-bout of resistance exercises (e.g., biceps and leg curls at 70% of each participants' 10-repetition maximum) for 20–25 min and evaluated pre- and post-exercise executive control via the Stroop task. In addition, Stroop task performance was assessed in separate sessions interleaved by a 30-min control condition (e.g., participants sat and read). The Stroop task is a speeded reaction time task wherein a series of colour names are printed in ink that is congruent (i.e., standard word-naming task) or incongruent (i.e., non-standard colour-naming task) to the word name. Results consistently report that RTs for the non-standard task are longer – and responses are more errorful – than the standard task, and is a result in part attributed to high-level executive demands related to inhibiting a pre-potent response. In Chang et al.'s (2014) study, RTs for stimuli-strings were measured via a handheld chronometer and the authors reported that post-test RTs in both exercise and control conditions were shorter than their pre-test counterparts; albeit with the magnitude of the improvement being larger in the exercise (i.e., 22%) than the control (i.e., 6%) condition. Accordingly, Chang et al. (2014) reported that a single-bout of exercise "…has a more beneficial effect on cognition that involves executive control." (p. 51). In addressing the improved post-exercise performance, it was proposed that a single-bout of exercise increases regional cerebral blood flow (rCBF) to executive-related cortical structures (for review see Verburgh et al., 2014) that optimize task-appropriate arousal and cortical efficiency (Lambourne and Tomporowski, 2010; see Dietrich and Audiffren, 2011 for arousal *during* exercise).

The positive benefit to executive control outlined above has been reported to be contingent on exercise duration. Both Lambourne and Tomporowski's (2010) and Chang et al.'s (2012) meta-analyses reported that short duration exercise sessions (i.e., < 20 min) produced a negative or null effect on cognitive and executive performance, whereas durations greater than 20 min produced a positive benefit (see also Brisswalter et al., 2002). Based on this evidence, it was proposed that the physiological changes necessary to promote an executive-related performance benefit require at least 20 min of sustained moderate-to-vigorous intensity physical activity. It is, however, important to recognize that some recent work has countered this proposal. Johnson et al. (2016) had older adults (mean age = 71.7 years) complete a Stroop task pre- and post- a 10- or 30-min aerobic or resistance training session (Borg Rating of Perceived Exertion between 13 and 14) and reported an immediate post-exercise RT improvement in the Stroop interference task – a result independent of exercise duration and type (i.e., aerobic and resistance). Johnson et al. concluded that a exercise duration as little as 10 min can improve executive control in older adults. Notably, the authors tempered extension of their findings to healthy young adults and suggested that older adults might have "… required less time in exercising to elicit cognitive improvements" (p. 597). Further, that the majority of previous work reporting a null exercise effect for durations less than 20 min may, in part, be accounted for by the fact that the Stroop and other 'executive' tasks (e.g., Tower of London, flanker, visual and acoustic oddball tasks) require not only high-level executive control but also non-executive functions such as receptive language, colour (Stroop task), and sequential memory (Tower of London) processing, as well as the top-down identification of perceptual novelty (i.e., oddball tasks). Accordingly, task involving conjoint executive and non-executive components may not provide sufficient resolution to detect subtle exercise-related executive changes following a short-duration exercise session.

The present investigation employed the antisaccade task to determine whether a 10-min single-bout of moderate-to-vigorous intensity aerobic exercise elicits a reliable executive-related performance benefit in healthy young adults. The antisaccade task requires that an individual complete a goal-directed eye movement (i.e., a saccade) mirror-symmetrical to the location of a visual stimulus (Hallett, 1978). Extensive behavioural and neuroimaging work from humans as well as electrophysiology from non-human primates has shown that antisaccades require the suppression of a stimulus-driven response (i.e., response suppression) and the visual remapping of a target's coordinates (i.e., vector inversion) (for review see Munoz and Everling, 2004) – constituent elements attributed to executive control. Moreover, the performance of directionally correct antisaccades has been linked to increased activation of executive-related frontoparietal networks (Ford et al., 2005; Weiler et al., 2015; Zhang and Barash, 2000; for review see Everling and Johnston, 2013) – cortical regions linked to modified activity following single-bout (Hiura et al., 2010; Seifert and Secher, 2011) and long-term (Colcombe et al., 2004; Voss et al., 2010) exercise. Further, we note that Everling and Johnston (2013) provide the heterodox view that the prefrontal cortex (PFC) provides excitatory inputs to the superior colliculus (SC) to facilitate behavioural goals; that is, task-dependent PFC activity encodes task-sets and task rules. As a result, an exercise-intervention may facilitate the task-appropriate modulation of PFC activity that serves to optimize antisaccade planning processes. Additionally, the hands- and language-free nature of antisaccades coupled with the temporal precision of eye-tracking (i.e., 360 Hz in the present investigation) make it an ideal task for determining whether a 10-min single-bout of aerobic exercise benefits executive-related oculomotor control.

Experiment 1 evaluated pro- (i.e., saccade to a veridical target location) and antisaccades performed in separate blocks at pre- and post-exercise assessments. The intervention entailed a single-bout of moderate-to-vigorous intensity aerobic exercise on a cycle ergometer (10 min at 60–85% of predicted maximum heart rate [HRmax] with 2.5 min each of warm-up and cool-down). In terms of research predictions, if aerobic exercise produces an immediate boost to executive-related oculomotor control then antisaccades should demonstrate a reliable post-exercise RT reduction and may exhibit decreased directional errors. In turn, equivalent antisaccade RTs at pre- and post-exercise assessments would indicate that a 10-min single-bout of aerobic exercise does not reliably improve executive-related oculomotor control. Notably, the prosaccade task was included here because such responses are stimulus-driven and are mediated via direct retinotopic projections within the SC (Wurtz and Albano, 1980); that is, prosaccades operate independent of the executive demands of response suppression and vector inversion (Pierrot-Deseilligny et al., 1995). Prosaccades therefore serve as a natural control to antisaccades because they are largely mediated via subcortical structures that are refractory to exercise-related modulation (see Colcombe and Kramer, 2003).

It is possible that a putative post-exercise reduction in antisaccade RT might relate to a practice effect; that is, from pre- to post-exercise assessments participants may better instantiate the task-set appropriate for antisaccade executive demands. To address that issue, Experiment 2 involved a separate corpus of participants wherein repeated pro- and antisaccade assessments were interspersed by a 'rest' interval (i.e., participants sat and read a magazine between pre- and post-break oculomotor assessments).

2. Methods

2.1. Experiment 1: participants

Fourteen participants (5 female; age range = 19–26 years of age) from the University of Western Ontario community volunteered for this research. Participants were right hand dominant (University of