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The long and winding road: Effects of exercise intensity and type upon sustained attention☆

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ABSTRACT

Aerobic exercise enhances the ability to sustain attention (peaking at moderate intensities) by stimulating noradrenergic activity, which affects the fronto-parietal attention network. Prior exercise studies examining attention have focused on the influence of exercise intensity, yet few studies have examined the influence of the type of exercise protocol administered. Here, we propose that sustained attention is greater during (a) moderate compared to low intensity exercise, and (b) moderate intensity exercise administered at a varied-load compared to a constant-load but the same overall intensity. To test this hypothesis, we recorded attentional focus in twelve male cyclists during a sustained attention to response task (SART) in four conditions; at rest, and during exercise at a low constant-, moderate constant- and moderate varied-load intensity. The change in α-amylase (indicative of the noradrenergic response) from saliva samples and activation of the right prefrontal and parietal cortices using near-infrared spectroscopy were recorded. The findings revealed that moderate intensity exercise at a constant-load leads to faster responses and less accuracy in the SART than rest and low intensity exercise. Moderate intensity exercise at a variable-load leads to even faster responses but with no loss of accuracy in the SART. This pattern of results is explained by a larger increase in salivary α-amylase during moderate (constant and varied) intensity cycling and higher activation in the dorso-lateral prefrontal cortex during the varied, but not the constant-load condition. In conclusion, we show that, in addition to exercise intensity, the type of exercise also has important implications upon attentional focus. While moderate intensity exercise generally enhances attentional focus, monotonous exercise at a constant-load may mask such benefits.

1. Introduction

Sustained attention, or vigilance, is the ability to maintain focus on relevant stimuli over a prolonged period of time [45] and is a crucial requirement for adequate cognitive performance [24]. Sustained attention depends on a large cortical network of frontal and parietal brain regions (including the dorso-lateral prefrontal cortex (dlPFC), the inferior frontal gyrus, the inferior parietal lobe and the intraparietal sulcus) with a right lateralized dominance [11, 12, 26, 49].

Activation of the fronto-parietal attention network is predominantly regulated through noradrenaline (NA) secretion from the locus coeruleus [3, 48]. The locus coeruleus is the major noradrenergic nucleus within the brain and has many excitatory projections to the cerebral cortex. Through NA pathways, the locus coeruleus regulates arousal in a quadratic (inversed-U) function [4]. In turn, arousal facilitates attention, such that moderate levels of NA activate the fronto-parietal network enhancing sustained attention [2].

Participation in physical (aerobic) exercise has been consistently shown to increase the concentration of plasma NA in humans [33]. The magnitude of NA release during exercise is influenced by both the intensity and duration of exercise [61]. During a short bout of incremental exercise, NA rises significantly above a certain intensity, labelled as the NA threshold [19] occurring around 75% of maximal oxygen uptake (VO_2max). The NA threshold is associated with other physiological thresholds such as the lactate and ventilatory thresholds (VT) (i.e. the points at which blood lactate and ventilation rise exponentially, respectively) [43]. The VT can be easily and non-invasively determined from collecting respiratory data [60]. Below the NA

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threshold, prolonged exercise can also lead to significant increases in plasma NA. For example, after 30 min of moderate intensity exercise (below VT), the concentration of plasma NA rises above the NA threshold [21]. Given that NA does not easily cross the blood–brain barrier, it is difficult to determine how increased NA concentration in the plasma during exercise impacts brain function. In the rat brain, Kitaoka et al. [25] applied micro dialysis in the hypothalamus and showed an increase in NA concentrations. In the human brain, Dalsgaard et al., [13] showed that increases in peripheral and central NA during exercise led to increased arterial NA concentration and NA in cerebrospinal fluid.

Due to the effects of exercise on NA secretion, it is expected that sustained attention is also affected. Empirical evidence supports this hypothesis. For example, Chmura, Nazar, & Kaciuba-Uścilko [9] showed that response times to an attentional task were faster as individuals approached their VT. In a study examining sustained attention before and after a single bout of moderate intensity running or rest, faster response times during an attentional task were observed after exercise, while no such benefit was shown after rest [44]. Using electroencephalography (EEG), larger P3 amplitudes (an electrophysiological marker of attention) were reported at frontal and parietal midline sites during exercise compared to rest, suggesting that moderate intensity exercise leads to an increased ability to activate the attentional network [8]. Additionally, similar P3 amplification and faster response times have been shown at intensities below the NA threshold (at 40% and 60% of VO_2max) when the exercise was maintained for 25 min [38]. In sum, evidence supports that exercise has a positive effect on attention primarily at moderate intensities.

Besides the intensity of exercise, there is surprisingly little evidence of how other exercise parameters influence attention such as the type of exercise protocol administered, that is, if the load is constant or varied. For example, cycling requires a continual repetitive effort when riding on a long flat road (equivalent to a constant-load), however varied levels of effort are required when riding undulating terrain (i.e. up and down hills, equivalent to a varied-load). Interestingly, the level of monotony of a task can have an important effect on sustained attention [14]. A task is considered monotonous if it has repetitive actions, and a relative absence of changes or variations in stimulation [7]. Such repetitive tasks correspond to exercise protocols administered in most studies whereby participants perform exercise at a constant-load (e.g. a given workload or percentage of VO_2max). In non-exercise contexts, monotony leads to a decrease in arousal and impairs sustained attention. For example, it was shown that manipulating monotony by varying the level of peripheral stimuli in a sustained attention to response task (SART) led to altered task performance [34]. In a driving task, individuals exposed to the same repetitive roadside visual stimulation reported a decrease in vigilance [27, 58]. In a more exercise-related context, the absence of variations in a robotic gait task induced higher brain activity (measured using EEG) typically related to sleepiness and low vigilance states [36].

Accordingly, the aim of this study was to examine the influence of the intensity and type of exercise upon sustained attention and associated underlying neurophysiological adaptations. Sustained attention was assessed using the SART [10], and two possible neurophysiological precursors were recorded. First, circulating levels of NA were inferred from salivary alpha-amylase (SAA) concentrations, indicative of noradrenaline synthesis [37, 42]. Second, activity of the fronto-parietal attention network was monitored using near infrared spectroscopy (NIRS), which measures changes in cortical oxygenated and deoxygenated hemoglobin (HbO and dHb). Previous work using NIRS has shown that this technique can be used to adequately evaluate cerebral oxy/deoxygenation status, and therefore activation of the attention network (i.e. lateral prefrontal or parietal regions) [5, 16, 17, 20]. Typically, it has been shown that increased HbO in frontal and/or parietal regions is well-correlated with behavioral indexes of performance in a vigilance task.

To manipulate the intensity of exercise, a prolonged cycling task was performed at a low or moderate intensity at a constant-load close to the VT. To manipulate the type of exercise (i.e. monotony), we contrasted the effects of moderate intensity exercise administered at a constant-load, with that of a variable-load (i.e. the same average intensity but with continuous variations in the pedaling load). A resting control condition, whereby participants simply sat on the bike without pedaling was also included.

We expected that moderate intensity exercise at a constant-load would lead to better performance during the SART, higher SAA concentrations and larger activation in the fronto-parietal regions (indicated by HbO and dHb) than in the low intensity and control (at rest) conditions. In addition, we expected that moderate intensity exercise administered at a varied-load would lead to better performance during SART, higher SAA concentrations and larger activation in the fronto-parietal regions than in the moderate intensity exercise at a constant-load condition.

2. Materials and methods

2.1. Participants

Twelve trained male cyclists participated in this study. Participants accumulated at least 100 km cycling per week and reported sleeping 7 to 8 h per night. During the experimental period, participants were asked to refrain from consuming psychostimulants (caffeine, alcohol and foods which elicit high concentrations of noradrenaline like bananas and chocolate). Participants completed a food/exercise/sleep diary (over the 48 h prior to each session) to verify compliance with the protocol constraints. The experimental sessions were held at the same time of day to minimize circadian influence upon arousal and separated by at least 48 h. The protocol was approved by the local research board. Following written and verbal explanation, all participants provided their written informed consent prior to participation in the study. The study was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.2. Procedure

Participants visited the laboratory on five occasions (one preliminary and four experimental sessions). In the preliminary session, participants completed questionnaires to assess their training status and to screen for attention deficits [35] and sleep disorders [15]. Participants' anthropometric and physiological data were recorded (see Table 1). Participants' VO_2max was determined during an incremental (25 watts/min) cycling test to exhaustion. Maximal power output (W) was determined from the last fully completed step of the test. During the test, metabolic data (i.e. oxygen uptake, carbon dioxide output, ventilation and the respiratory exchange ratio) were continuously recorded using a gas analyzer (Oxycon Alpha, Erich Jager, Mijinhadt b.v., The Netherlands) and heart rate (HR) was collected using a thoracic belt and a watch (Polar RS800, Polar Electro Oy, Kempele, Finland).

Table 1
Anthropometric and physiological description of the participants. HR max = heart rate maximum. bpm = beats per minute. VT = ventilatory threshold. VO_2max = maximum oxygen uptake.

	Mean (SD)
Age (yrs)	27.8 (2.0)
Height (cm)	176.5 (7.0)
Weight (kg)	69.8 (6.6)
HR max (bpm)	185 (10.9)
Workload at VT (watts)	230 (54.4)
VO_2max (mL/min/kg)	57.4 (3.3)