Neuropsychologia 68 (2015) 71–81

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Pushing to the limits: The dynamics of cognitive control during exhausting exercise

Cyril Schmit [a,b,*], Karen Davranche [d], Christopher S. Easthope [a,c], Serge S. Colson [a], Jeanick Brisswalter [a], Rémi Radel [a]

[a] Laboratoire LAMHESS (EA6309), Université de Nice Sophia-Antipolis, France
[b] Institut National du Sport, de l'Expertise et de la Performance (INSEP), Département de la Recherche, Paris, France
[c] Spinal Cord Injury Centre, Balgrist University Hospital, Zurich, Switzerland
[d] Aix Marseille Université, CNRS, LPC UMR 7290, FR 3C FR 3512, 13331 Marseille cedex 3, France

ARTICLE INFO

Article history:
Received 26 May 2014
Received in revised form
25 November 2014
Accepted 7 January 2015
Available online 8 January 2015

Keywords:
Cognitive functions
Response inhibition
Physical exercise
Cerebral oxygenation
Exhaustion

ABSTRACT

This study aimed at investigating concurrent changes in cognitive control and cerebral oxygenation (Cox) during steady intense exercise to volitional exhaustion. Fifteen participants were monitored using prefrontal near-infrared spectroscopy and electromyography of the thumb muscles during the completion of an Eriksen flanker task completed either at rest (control condition) or while cycling at a strenuous intensity until exhaustion (exercise condition). Two time windows were matched between the conditions to distinguish a potential exercise-induced evolutive cognitive effect: an initial period and a terminal period. In the initial period, Cox remained unaltered and, contrary to theoretical predictions, exercise did not induce any deficit in selective response inhibition. Rather, the drop-off of the delta curve as reaction time lengthened suggested enhanced efficiency of cognitive processes in the first part of the exercise bout. Shortly before exhaustion, Cox values were severely reduced – though not characteristic of a hypofrontality state – while no sign of deficit in selective response inhibition was observed. Despite this, individual's susceptibility to making fast impulsive errors increased and less efficient online correction of incorrect activation was observed near exhaustion. A negative correlation between Cox values and error rate was observed and is discussed in terms of cerebral resources redistribution.

1. Introduction

It is now well-accepted that physical exercise has a positive effect on basic cognitive functions (Tomporowski, 2003; Lambourne and Tomporowski, 2010), however its impact on higher cognitive processes (*e.g.* selective inhibition) is less clear. According to the different meta-analyzes on exercise and cognition, it seems that exercise would lead to a rather small positive effect on cognitive functioning due to large variations of the reported results (Chang et al., 2012; McMorris et al., 2011). It has been proposed that exercise intensity would be the most important factor to explain this variability. Specifically, an inverted-*U* function has been suggested in such a form that exercise above a certain intensity is no longer beneficial to cognitive functioning (McMorris and Hale, 2012). In other words, while moderate exercise is associated with a positive effect, intense exercise (*i.e.* above the second ventilatory threshold, VT2) is associated to a null or negative effect on cognitive functioning. This view has been supported by the main theoretical models. According to the arousal-cognitive performance (Yerkes and Dodson, 1908), the catecholamine (Cooper, 1973; McMorris et al., 2008) and the reticular-activating hypofrontality (Dietrich, 2003, 2009; Dietrich and Audiffren, 2011) theories, intense exercise, by inducing high levels of arousal, increasing neural noise, or down-regulating prefrontal cortex activity, respectively, is predicted to impede higher cognitive processes.

Evidence of the detrimental effect of intense exercise mostly come from studies using incremental protocols in which the effects of exercise, probed at the end of the exercise, are confounded with the effect of exhaustion (*e.g.* Ando et al., 2005; Chmura and Nazar, 2010; McMorris et al., 2009). The present study aimed to dissociate the effect of the intensity from the state of exhaustion using a steady state intense exercise performed until exhaustion. Exhaustion is a psychophysiological state concluding a fatigue development process. It is a predictable consequence to any strenuous exercise. The state of exhaustion can also be considered as the time spent on the task. In a concomitant realization of a choice reaction time task and a fatiguing submaximal contraction,

* Correspondence to: Institut National du Sport, de l'Expertise et de la Performance. 11, avenue du Tremblay, 75 012 Paris, France.
E-mail address: cyril.schmit@insep.fr (C. Schmit).

http://dx.doi.org/10.1016/j.neuropsychologia.2015.01.006
0028-3932/

Lorist et al. (2002) showed that the more the time-on-tasks elapsed, the more error rate and force variability of hand muscles increased, suggesting an increasing detrimental effect of the dual-task on the dual-performance.

The detrimental effect of exercise on cognition occurring near exhaustion can be explained as neural competition for the limited cerebral resources between different centers of the brain (Dietrich, 2003, 2009; Dietrich and Audiffren, 2011). Specifically, the hypofrontality theory predicts that the prefrontal cortex (PFC), in response to the development of muscular fatigue, would be down-regulated to favor the allocation of resources to motor areas, which would in turn result in weaker cognitive functioning. The resource redistribution hypothesis has been supported by animal studies assessing cerebral activity during exercise. Tracing regional cerebral blood flow and local cerebral glucose utilization as indexes of cerebral activity showed a selective cortical and subcortical recruitment of brain areas during exercise (Delp et al., 2001; Gross et al., 1980; Holschneider et al., 2003; Vissing et al., 1996). Specifically, while motor and sensory cortices, basal ganglia, cerebellum, midbrain and brainstem nuclei were consistently activated at high intensities, the frontal cortex rather showed signs of deactivation. Positron emission tomography studies have also provided a similar pattern of findings in human (Tashiro et al., 2001, Kemppainen et al., 2005). If such neural balance may rationalize down-regulated cognitive performances during exercise (Dietrich and Audiffren, 2011), previous result remain based on an instantaneous description of the neural pattern during exercise, which does not inform about changes related to the proximity of exhaustion.

Near-infrared spectroscopy (NIRS) is a continuous tissue-monitoring technique which is able of tracking cerebral oxygenation (Cox) during exercise due to its relative robustness during movement (see Perrey, 2008). The NIRS method has been validated and correlates highly with both electro-encephalographic and functional magnetic resonance imaging responses (Timinkul et al., 2010; Toronov et al., 2001). NIRS studies during exercise have shown a very dynamic Cox pattern. A meta-analysis by Rooks et al. (2010) proposes an intensity based account with the second ventilatory threshold as the critical reversing point in the inverted-*U* relation between exercise intensity and PFC oxygenation determined through oxyhemoglobin concentration [HbO_2]. Nevertheless, this pattern is specific to untrained participants, as trained participants do not show any [HbO_2] decline at high intensities. In addition, most of the studies reviewed employed incremental protocols. In studies that push participants until exhaustion, results suggest that [HbO_2] reduction may be related to the individual time course to exhaustion. Timinkul et al. (2008) reported an individual timing of Cox desaturation, occurring before VT2 for some participants and after for others. During steady intense exhausting exercise, Shibuya et al. (2004a,b) reported Cox patterns identical to those observed in incremental exercise (e.g., Bhambhani et al., 2007; Rupp and Perrey, 2008). However, the paucity of the exercise-NIRS studies on intense as well as prolonged exercise to exhaustion in humans cannot ensure the validity of a fatigue-based PFC deactivation hypothesis.

The second aim of the present study was to investigate concurrent changes in cognitive performance and Cox in PFC while performing strenuous exercise until volitional exhaustion. More specifically, the protocol was designed to determine whether cognitive performance and Cox follow a similar dynamic. In an initial period of intense exercise, it was anticipated that cognitive performance would be facilitated and Cox elevated compared to the same initial period at rest. Then, in a critical period occurring just before exhaustion, we expected a decrease in cognitive performance and a drop of PFC [HbO_2] in comparison to the same period at rest. Cognitive performances were assessed using a modified version of the Eriksen flanker task (Eriksen and Eriksen, 1974), consisting in overcoming the irrelevant dimension of the stimulus to give the correct response, to probe the efficiency of selective response inhibition. The flanker task has been largely used to investigate the effects of exercise on cognitive control (Davranche et al., 2009a,b; McMorris et al., 2009; Pontifex and Hillman, 2007). Although mean RT and average error rate do provide valuable information relative to cognitive processes, more-detailed data analyzes uncover modulations that the sole consideration of central tendency indices cannot reveal. Indeed, combined to RT distribution analyzes, conflict tasks have proved to be powerful for assessing the processes implemented during decision-making tasks while exercising (Davranche and McMorris, 2009; Davranche et al., 2009a,b; Joyce et al., 2014).

On a substantial amount of trials, although the correct response was given, a subthreshold electromyographic (EMG) activity in the muscles involved in the incorrect response could be observed. Such subthreshold EMG activities, named “partial errors”, reflect incorrect action impulses that were successfully corrected in order to prevent a response error (Hasbroucq et al., 1999). To evaluate the efficiency of the cognitive control during exercise, electromyographic (EMG) activity of response effector muscles were monitored to estimate the number of partial EMG errors. In order to measure Cox, NIRS recording was centered on the right inferior frontal cortex (rIFC) as this brain area is a main region involved in the brain network supporting the inhibition function (Aron et al., 2004, 2014), and has been described as the most responsive region while performing the Eriksen flanker task (Hazeltine et al., 2000). Additionally, the distribution-analytical technique and the delta plot analysis (Ridderinkhof, 2002; Ridderinkhof et al., 2004) were used to assess the efficiency of cognitive control and the propensity to make fast impulsive reactions through the analyzes of the percentage of correct responses (CAF) and the magnitude of the interference effect (delta curve) as a function of the latency of the response (van den Wildenberg et al., 2010). If exhausting exercise impairs the efficiency of cognitive control, the drop-off of the delta curve should be less pronounced in the terminal period than in the initial period. If the propensity to commit impulsive errors increases before exhaustion, more errors are expected for fast RT trials on distributional analyzes of response errors.

2. Method

2.1. Participants

Fifteen volunteers took part in this experiment. They were mostly classified as untrained following the $\dot{V}O_2$ max criteria of de Pauw et al. (2013) and had basic cycling experience (<1 h a week). Informed written consent was obtained according to the declaration of Helsinki. Participants' anthropometrical and

Table 1
Anthropometrical and physiological characteristics of participants.

Variables	Mean ± SD All	Women	Men
Sample size	15	5	10
Age [years]	22.1 ± 0.6	23.2 ± 1.2	21.5 ± 0.6
Height [cm]	175.9 ± 2.6	166.3 ± 1.8	180.7 ± 2.6
Body mass [kg]	66.5 ± 3.1	52.9 ± 2.1	73.3 ± 2.3
$\dot{V}O_2$ max [ml kg^{-1} min^{-1}]	44.5 ± 1.9	45.2 ± 2.9	44.1 ± 2.6
Maximal HR [bpm]	178 ± 2.6	180 ± 1.9	177 ± 3.0
MAP [W]	261.3 ± 14.2	204.3 ± 10.3	290.2 ± 12.2

Results are presented as the mean group ± SD.
Notes. SD = standard deviation; MAP = maximal aerobic power; $\dot{V}O_2$max = maximal oxygen consumption; HR = heart rate.