Where are the limits of the effects of exercise intensity on cognitive control?

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Abstract

Purpose: This study aimed to investigate whether workload intensity modulates exercise-induced effect on reaction time (RT) performances, and more specifically to clarify whether cognitive control that plays a crucial role in rapid decision making is altered.

Methods: Fourteen participants performed a Simon Task while cycling 20 min at a light (first ventilatory threshold, VT 1e20%), moderate (VT1), or very hard (VT 1e20% + 20%) level of exercise.

Results: After 15 min of cycling, RTs are faster than during the first 5 min of exercise. This benefit does not fluctuate with the intensity of exercise and enlarges as RT lengthens. Despite a numerical difference suggesting a greater facilitation during moderate exercise (e16 ms) than during a light exercise (e10 ms), the benefit is not statistically different. Interestingly, we did not observe any signs of worsening on RT or on accuracy during very hard exercise.

Conclusion: Cognitive control is extremely robust and appears not to be affected by the intensity of exercise. The selective inhibition and the between-trials adjustments are effective from the beginning to the end of exercise, regardless of the workload output.

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Keywords: Between-trials adjustments; Intensity level; Reaction time distributional; Simon Task

1. Introduction

When cognitive performance is assessed while exercising, a beneficial influence of acute moderate exercise is generally reported. However, recent studies suggest that above a certain intensity level, cognitive functioning could be disrupted during exercise and could particularly impair higher order cognitive processing also referred to as cognitive control or executive functions such as response inhibition, selective attention, and task flexibility which are crucial elements in decision-making. According to the transient hypofrontality theory, physical exercise generates a massive neural activation which contributes to the recruitment of motor units, sensory input integration, and regulation of the autonomic systems. Given a limited resource capacity, this huge request induces a competition for resources that would be expected to result in a diminution of the resources allocated to brain structures which are not directly involved in motor control (areas of the prefrontal cortex and, perhaps, the amygdala).

Nevertheless, to date, the accumulated evidence is equivocal and provides an unclear picture of the relationship between exercise intensity and cognitive control. Using a Simon Task, Davranche and McMorris found that selective response inhibition was impaired by moderate acute exercise (20-min steady-state cycling at ventilatory threshold intensity corresponding to an average of 77% 4% of maximal heart rate (HRmax). The Simon Task is a classic paradigm used to study how irrelevant spatial relationships between stimuli and responses affect human decisions. In the standard version of this task, participants have to choose between a left- and a right-hand key press according to a non-spatial attribute of a
stimulus which is presented on the left or on the right of a fixation point. Participants are required to respond, as quickly and accurately as possible, by selecting the relevant feature of the stimulus (e.g., the color) and inhibiting the irrelevant feature (the spatial location) of the same stimulus. The performance expressed both in terms of error rate and mean reaction time (RT) is better when the required response corresponds spatially to the irrelevant stimulus location (congruent association, CO) than when it does not correspond (incongruent association, IN). This phenomenon is known as the Simon effect (RT on incongruent trials minus RT on congruent trials) and is assigned to the emergence of a conflict between the activation of the incorrect response (associated with the irrelevant information) and the activation of the correct response (associated with the relevant information) which delays the response execution. Similar impairment have also been observed with elite white-water athletes\(^6\) paddling at a moderate intensity (75% HR\(_{\text{max}}\)), suggesting that selective response inhibition was worse when the Simon Task was performed concurrently with a moderate paddling exercise compared with a light paddling exercise. In contrast, McMorris et al.\(^8\) failed to observe any deteriorations of selective response inhibition despite very high physiological stress (i.e., 80% of maximal aerobic power, MAP). The intensity of exercise is probably a key variable in determining the presence or absence of a beneficial effect of exercise on cognitive control. The nature of the cognitive task is also critical. Cognitive processes appear to be differently altered by exercise-induced effects. Davranche and McMorris\(^8\) suggested that the effect of exercise seems to be specific, rather than general, and can probably not be generalised across different cognitive functions even if these functions involve similar specific regions of the brain like prefrontal-dependent cognitive tasks. Future studies, using different prefrontal-dependent cognitive tasks in the same protocol, should be conducted while exercising to test this assumption.

RT distribution analyses have proved to be powerful for assessing the processes implemented during decision-making tasks and in the Simon Task in particular. According to dual-route models of information processing,\(^{12-14}\) this finding results from a conflict between an automatic and rapid response impulse (triggered by the spatial location) and a slower, deliberately controlled response to the pertinent stimulus information (the color).

Using a Simon Task performed while cycling at light, moderate, and very hard level of exercises, the present study attempts to clarify past findings and to contribute to a better understanding of the interaction between exercise intensity and cognitive control processes. During light intensity exercise, we anticipate that cognitive performance will be facilitated (faster RT without change in accuracy) and cognitive control will continue to be fully efficient. If the intensity of exercise is a critical consideration for cognitive control, as the intensity of exercise increases to a moderate level and/or a very hard level of exercise, we should observe a decrease in cognitive performance (or at least a reduced benefit of exercise).

2. Methods

2.1. Participants

Fourteen undergraduate students were recruited in exchange for course credits through the research participation system of the Sport Sciences Department of the University. All of our participants were regularly involved in endurance activities at least once a week. They were regularly involved in sport activities and could be considered as moderately trained subjects. Written informed consent was obtained from all subjects prior to their participation. This study was approved by the local ethical committee. Anthropological and physiological characteristics of the participants are summarized in Table 1.

2.2. Procedure

The subjects were required to visit the laboratory during 4 different days. As the tests could be influenced by circadian rhythms, testing for each participant was carried out at the same time of day as their previous session. The lag-time between each visit ranged from 2 to 16 days. Participants were instructed to avoid doing any vigorous exercise during the last 24 h and to abstain from drinking coffee 2 h before each visit.

The first visit served to familiarize the participants with the cognitive task and to collect their anthropometrical and physiological characteristics. During the familiarization, subjects performed four blocks of 200 trials of the Simon Task. Additional blocks were performed, if necessary, until reaching the following learning criteria: a) RT intra-block variability below 5%, b) RT variability with the previous block below 5%, c) mean RT less than 600 ms, and d) response accuracy greater than 85%.

Five min after the Simon Task training, participants performed a maximal incremental exercise test to determine maximal oxygen consumption and power at the first ventilatory threshold (VT\(_1\)). The test was performed on an electronically braked cycle-ergometer adjusting the power to the pedal frequency (Brain-bike NeuroActive; recumbent bike, BE-7216, Taiwan, China). After a 4-min warm-up at light

<table>
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<tr>
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</table>

Abbreviations: HR = heart rate; VO\(_2\)max = maximal oxygen consumption; MAP = maximal aerobic power; VT\(_1\) = first ventilatory threshold.
intensity (women: 70 W; men: 80 W), an increase of 10 W was operated every 30 s until volitional exhaustion (i.e., participants’ deliberate choice or incapacity to maintain a pedaling frequency above 50 rotations per minute). Oxygen consumption (VO2, mL/kg/min) and ventilation (VE, L/min) were recorded using a breath by breath gas analyzer previously validated by Nieman et al.15 (Fitmate Pro; COSMED, Miami, FL, USA) and HR was monitored using a Polar system (RS800CX; Polar Electro Oy, Kempele, Finland). The VT1, defined as the point during exercise at which pulmonary ventilation increases disproportionately to oxygen consumption, was determined according to Wasserman et al.16 Each experimental session was then determined according to this value. According to Whipp,17 the power output at which participants reached VT1 was considered to represent a moderate intensity level of exercise, while the light level of exercise corresponded to an intensity below VT1 (i.e., VT1 – 20%) and the very hard level of exercise corresponded to VT1 + 20%.

During the three experimental sessions, participants were required to complete two blocks of 200 trials (each block was about 4 min in length) while exercising for 20-min exercise session at a light, moderate, or very hard level (Fig. 1). The order of the three experimental sessions was counterbalanced. Each session began with a 100-trial training block. Then, participants warmed up by pedaling at a low intensity for 3 min (women: 70 W; men: 80 W). After that the power output was increased for 2 min until reaching the intensity corresponding to the experimental condition. The first block of the cognitive task (200 trials) started exactly 5 min after the onset of the exercise. HR was measured at the end of the first block and the cycling power output was then adjusted to keep the same HR all along the rest of the session in order to keep physiological constraints constant. The second block (200 trials) started exactly 15 min after the onset of the exercise. Participants stopped exercise when the block was completed and engaged in a recovery protocol. Fig. 1 illustrates the protocol of the experimental sessions.

2.3. Cognitive task

The three experimental sessions were performed on a cycle ergometer (Brain-bike NeuroActive; Motion Fitness Co., Rolling Meadows, IL, USA) equipped with a handlebar and soft padding supports to comfortably support forearms. Two thumb response keys were fixed on the top of the right and left handle grips. Two light-emitting diodes (LEDs), separated by 24 cm, were positioned at both sides of a black panel placed 1 m in front of the participant. Each trial started with the illumination of a central blue gaze-fixation LED followed by the illumination of either the red or the green LED. The delivery of a response turned off the stimulus and the next trial began after a constant 800 ms inter-stimulus interval (ISI). If 1 s elapsed without a response, the LED extinguished and the next trial began after the ISI. Participants were asked to exert a press, as quickly and accurately as possible, on the right or on the left response key as soon as one of the LEDs lit up. The light could be green or red and could be delivered either to the left or to the right side. The response was given, by pressing the appropriate response key, according to the color of the LED (task-relevant attribute) whatever the location of the LED (the task-irrelevant attribute). Half of the participants had to exert a press with the left thumb when the LED was red and a press with the right thumb when the LED was green, the other half of the participants were to perform the reverse stimulus-response mapping. There were two types of trials in each block: CO (50%) and IN (50%). The CO trials during which the spatial location of the stimulus corresponded to the task-relevant aspect of the stimulus (e.g., left stimulus/left response), and the IN trials in which the spatial location of the stimulus corresponded to the opposite spatial location of the response (e.g., left stimulus/right response).

2.4. Data analysis and statistics

RT less than 100 ms or higher than 1500 ms, considered as anticipated responses and omissions respectively, were excluded from further analyses. RT distributions and curve accuracy functions (CAFs) were conducted to closely examine the temporal dynamics of information processing and to dissociate the activation of incorrect responses and its subsequent selective suppression.18 The analyses of the percentage of correct responses (CAFs) and the magnitude of the interference effect (delta curve) as a function of RT allows for the assessment of both the initial phase linked to an individual’s susceptibility to making fast impulsive errors (early automatic response activation) and, the later phase associated with the efficiency of the cognitive control (build-up of a top-down response suppression mechanism). In each condition, the RT distribution was obtained using individual RTs “vincentized” into five equal-size speed bins (quintiles) for CO and IN trials separately. Delta plots were constructed by plotting

![Fig. 1. Schematic representation of the experimental sessions consisting in performing a Simon Task during 20 min at a light (VT1 – 20%), moderate (VT1), or very hard (VT1 + 20%) level of exercise. VT1 = the first ventilatory threshold.](image-url)
3. Results

3.1. HR

An ANOVA involving intensity (light, moderate, and very hard) as within-subject factors revealed a main effect of intensity on mean HR (F(2, 26) = 111.69, p < 0.0001, \( \eta^2 = 0.90 \)). HR increased with the intensity of exercise. During light, moderate, and very hard intensity exercise, HR was, respectively, 135 ± 4 bpm, 148 ± 4 bpm, and 165 ± 3 bpm, which corresponds to 74%, 81%, and 90% of HR_{max}.

*Because the data were not normally distributed, the arcsine transformations were applied on the error rate.*

3.2. RT

Results showed a main effect of congruency (F(1, 13) = 25.24, p < 0.001, \( \eta^2 = 0.66 \)) with longer RT for IN trials (344 ± 8 ms) than for CO trials (328 ± 8 ms). There was also a main effect of period (F(1, 13) = 34.64, p < 0.0001, \( \eta^2 = 0.73 \)). After 15 min of cycling, participants were faster (329 ± 8 ms) than during the first 5 min of exercise (343 ± 8 ms) (Fig. 2). No other main effect or interaction was significant. Collectively, these findings suggest that a facilitating effect of exercise can be observed after 15 min of exercise, and this benefit did not fluctuate with the intensity of exercise (F(2, 26) = 1.71, p = 0.21, \( \eta^2 = 0.21 \)). There was no evidence of an interaction between period and intensity (F(2, 26) = 0.81, p = 0.45, \( \eta^2 = 0.06 \)).

3.3. Decision error

Analysis showed the classic effect of congruency illustrating the prevalence of more errors for IN trials (10.46% ± 0.9%) than for CO trials (7.12% ± 1.7%) (F(1, 13) = 6.27, p < 0.32, \( \eta^2 = 0.73 \)). The main effect of period was not significant (F(1, 13) = 0.48, p = 0.50, \( \eta^2 = 0.04 \)), nor was the interaction with any other factor. These findings suggest that the benefit of exercise is not due to a speed–accuracy tradeoff.

3.4. Distributional analysis

Separate ANOVAs involving intensity (light, moderate, and very hard), congruency (CO vs. IN), period (5 min vs. 15 min), and quintiles as within-subject factors were performed on RT distributions and CAF to determine whether curves diverge according to the period and the intensity.

Regarding RT distributions, results confirmed a main effect of congruency (F(1, 13) = 30.16, p < 0.001, \( \eta^2 = 0.70 \)) and a main effect of period (F(1, 13) = 81.03, p < 0.0001, \( \eta^2 = 0.86 \)) as previously observed on mean RT. More interestingly, the analysis showed an interaction between period and quintile (F(4, 52) = 7.30, p < 0.05, \( \eta^2 = 0.36 \)) which revealed that the benefit induced by exercise increases as RT lengthens (Fig. 3). No other main effect or interaction was significant. Collectively, these findings suggest that a facilitating effect of exercise can be observed after 15 min of exercise, and this benefit did not fluctuate with the intensity of exercise. There was no evidence of an interaction between period and intensity.
significant. There is no evidence of interaction between period and intensity and quintile \((F(8, 104) = 0.11, p = 0.99, \eta^2 = 0.01)\) or between period, intensity, congruency, and quintile \((F(8, 104) = 0.59, p = 0.78, \eta^2 = 0.04)\).

Regarding CAF, the classic interaction between congruency and quintile was significant \((F(4, 52) = 27.94, p < 0.0001, \eta^2 = 0.68)\) and illustrated the strength of the automatic response capture. In the initial phase (first quintile), the frequency of fast errors is higher for IN trials compared to that for CO trials \((83.0\% \pm 1.7\% \text{ vs. } 99.0\% \pm 0.3\% \text{ of accuracy}, \text{respectively})\). This pattern is related to an individual’s susceptibility to produce incorrect responses, which is automatically activated by irrelevant information and leads to the correct answer for CO trials and an error for IN trials. Interestingly, the propensity to commit fast errors is not influenced by intensity \((F(8, 104) = 0.94, p = 0.49, \eta^2 = 0.07)\) or period of exercise \((F(4, 52) = 1.01, p = 0.37, \eta^2 = 0.08)\) or both \((F(8, 104) = 0.32, p = 0.96, \eta^2 = 0.02)\) (Fig. 4).

### 3.5. Post-conflict and post-error adjustments

An ANOVA with intensity, period, and correctness of the preceding trial (correct vs. error) as within-subject factors was conducted to assess post-error adjustments. Results showed a post-error slowing effect \((F(1, 13) = 35.43, p < 0.0001, \eta^2 = 0.73)\), with RT after an error slower \((367 \pm 12 \text{ ms})\) than after a correct trial \((333 \pm 8 \text{ ms})\). No other main effect or interaction was significant, suggesting that the between-trials adjustments pattern after an error is not affected by exercise and does not fluctuate with exercise intensity.

A second ANOVA involving intensity, period, congruency on trial \(n\) (CO vs. IN), and congruency on the preceding trial \(n - 1\) (<<CO vs. <<IN) as within-subject factors was conducted to assess the post-conflict adjustment. Results confirmed the effect of period and the effect of congruency reported in the RT section. As expected, the interaction between the congruency on trial \(n\) and the congruency on trial \(n - 1\) was significant \((F(1, 13) = 66.47, p < 0.0001, \eta^2 = 0.84)\). RT was slower for CO trials when the preceding trial was IN \((339 \pm 8 \text{ ms})\) compared to when the preceding trial was CO \((316 \pm 8 \text{ ms}, p < 0.001)\). By contrast, RT was faster for IN trials when the preceding trial was IN \((331 \pm 7 \text{ ms})\) compared to when the preceding trial was CO \((348 \pm 8 \text{ ms}, p < 0.001)\). Interestingly, the analysis showed an interaction between intensity, period, congruency on trial \(n\), and congruency on the preceding trial \(n - 1\) \((F(2, 26) = 5.21, p < 0.05, \eta^2 = 0.29)\). Examination of the nature of this interaction revealed that the post-conflict adjustments are not
affected by exercise except at very hard intensity (Fig. 5). At this intensity, RT of all the type of trials (i.e., no matter what the congruence of the trial $n$ and $n-1$) are enhanced after 15 min of exercise, however the facilitation is larger for the CO trials preceded by a CO trial compared to all others trials.

4. Discussion

Using a Simon Task performed while cycling, the aim of this paper was to examine whether workload intensity modulates the exercise-induced effect on RT performance, and more specifically to clarify whether cognitive control that plays a crucial role in rapid decision making is altered. After 15 min of cycling, results showed that participants are faster than during the first 5 min of exercise. This benefit does not fluctuate with the intensity of exercise and enlarges as RT lengthens. Despite a numerical difference suggesting a greater facilitation during moderate exercise ($-16\text{ ms}$) than during a light exercise ($-10\text{ ms}$) (Fig. 2), the benefit is not statistically different. Interestingly, we did not observe any signs of worsening on RT or on accuracy during very hard exercise. The present results showed that cognitive control is extremely robust and appears not to be affected by the intensity of exercise. The selective inhibition and the between-trials adjustments are effective from the beginning to the end of exercise, regardless of the workload output ($VT_1 - 20\%$, $VT_1$, or $VT_1 + 20\%$).

4.1. Exercise-induced effect and cognitive control

The literature on the effects of exercise on cognitive performance shows much heterogeneity in the results. Even if some evidence suggests an impairment of cognitive control during exercise, the effect of exercise can probably not be generalised across different cognitive tasks even if these tasks involve similar specific regions of the brain like prefrontal-dependent cognitive tasks. Across the different indicators of cognitive performance extracted from the present study, exercise intensity did not affect the benefit of exercise on cognitive performance. By comparing performance after 15 min of exercise to performance in the first 5 min of exercise, the present experiment allowed us to assess the effect of exercise with a particularly relevant baseline measurement, which highlighted a constant exercise-induced benefit independent of workload intensity. Not only is RT performance enhanced (i.e., participants were faster to respond after 15-min cycling than at the beginning), but the within-trial inhibitory processes (i.e., interference size) and the inter-trials adjustments (i.e., post-error and post-conflict) are also fully effective. The present results suggest that selective response inhibition appears to be more robust than has been suggested in the literature. In contrast to the predictions of the inverted-U model or the hypofrontality theory, cognitive control during very hard exercise is as effective as during moderate exercise. The manner in which prefrontal-dependent cognitive tasks are influenced by exercise is, in all probability, related to the specificity of the cognitive task. Global hypotheses have been formulated on prefrontal-dependent cognitive tasks, however the most striking examples of decline of cognitive performance during exercise were reported on working memory task, cognitive flexibility, and planning task. A general statement concerning a decline in cognitive performance during exercise cannot be done by inferring from specific cases. Exercise-induced impairments could be restricted to specific executive functions, such as reasoning, working memory, or cognitive flexibility, and may not be generalised to cognitive control more broadly.

4.2. Partial electromyography (EMG) error and negative-going delta-plots

The lack of evidence of deterioration of cognitive control is inconsistent with previous results reporting an impairment of selective inhibition during a Simon Task. In the standard version of this task, participants are required to respond, as quickly and accurately as possible, and RT is usually reported to be worse when relevant and irrelevant information are mapped to different responses, than when they correspond to the same response. This finding results from a conflict between an automatic and rapid response impulse (triggered by the spatial location) and a slower, deliberately controlled response to the pertinent stimulus information (the color). The automatic activation is initially strong, but gradually decreases over time with the development of a slow inhibition. If we consider that this incremental inhibition takes time to setup, the slower responses benefit more from this suppression than the fast ones. This has been proposed to account for the gradual diminution of the Simon effect as RT lengthens. Consequently, we can assume that when response inhibition is proficient, a pronounced levelling off of the delta plot (reflecting a reduction of the interference effect for slower responses) should be observed. In this framework, based on detailed analysis of RT distributions, Davranche and collaborators reported a less pronounced levelling off the delta-plots during acute moderate intensity exercise. This result

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\textsuperscript{a} Delta plots were constructed by calculating the Simon effect (average of difference between RT in IN and RT in CO trials) as a function of the response speed.

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\textbf{Fig. 5.} Mean reaction time (RT) in millisecond in the very hard intensity condition during the 5-min (left) and 15-min (right) period for congruent (CO) and incongruent (IN) trials according to the compatibility of the preceding trial $n - 1$. $<<\text{CO} =$ congruent; $<<\text{IN} =$ incongruent.
was replicated and observed both while cycling (at moderate intensity vs. rest) and paddling (at a light intensity vs. moderate intensity). Referring to the activation-suppression hypothesis, the authors interpreted this decrease of the delta-plots during exercise as an impairment of selective inhibition.

In conflict tasks, many correct response trials contain sub-threshold muscle activity in the incorrect hand, a so called partial EMG error. These partial EMG errors represent incorrect action impulses that are successfully corrected in order to prevent a response error. Such partial EMG errors require a strong inhibitory control not to lead to an overt error and the delta plots calculated for partial EMG errors appear hugely negative-going. However, Burle et al. recently demonstrated that once partial EMG errors were removed, the delta plots were almost flat. Partial EMG errors thus play a crucial role in determining the shape of a negative-going delta-plot. Considering Davranche and collaborators’ results regarding this new data, one may speculate that change in the levelling off the delta-plots reported during exercise could in fact reflect a change in the propensity of partial EMG errors more than a deficit in inhibition. Independently of the ability to suppress the automatic response generated by task-irrelevant aspects of the stimulus, we can speculate that during exercise fewer partial EMG errors appear, which leads to a less negative-going delta plots. Future research may attempt to clarify this issue.

4.3. Participants level of fitness and exercise duration

According to the meta-analysis by Chang et al., fitness level could be a crucial factor as a negative effect of exercise on simultaneous cognitive performance was only found for studies including participants with low fitness levels. In line with this finding, a recent study by Labelle et al., manipulating exercise intensity and controlling for fitness level, revealed that lower fit individuals showed more instability in performance of an inhibition task than higher fit individuals during high intensity exercise. Hüttermann and Memmert reported similar results when comparing cognitive performance for expert team sports athletes and non-athletes on visual attentional performance under different exercise intensities (50%, 60%, and 70% HRmax). Athletes were able to maintain cognitive performance independently of workload intensity while non-athletes showed increases in cognitive performance up to a certain intensity level before decreases were observed.

Chang et al. explained that participants with lower fitness would need more resources when conducting exercise, and would therefore have less resources available for cognitive performance. However, McMorris proposed a different explanation to account for why high fit participant demonstrated a positive effect of exercise while low fit participants showed an inverted-U effect. He argued that the perception of the physiological stress rather than fitness itself may explain why the level of fitness of the participants modulates the acute exercise-cognition relationship. If we consider that high intensity exercise is more anxiety provoking for low fit individuals than for high fit individuals, who are not really concerned about exercising maximally, it is reasonable to assume that feedback of the autonomic nervous system to the CNS and/or perception of the effort will be extremely different. Consequently, differences in plasma concentrations of lactate, adrenaline, and noradrenaline are expected at any level of exercise, which could account for evidence that fitness level acts as a moderator in exercise-cognition relationship. These proposed explanations deserve more investigation and should be tested in future studies.

Both explanations are actually compatible with evidence from cerebral oxygenation recording during exercise indicating that exercise intensity increases lead to a drop in oxygenated hemoglobin, but only for untrained subjects. Considering that all of our participants were regularly involved in sport activities and could be considered as moderately trained subjects, the present results provide an indirect argument in favor of the role of physical fitness in the maintenance of cognitive performance during exercise.

Even with trained athletes, the maintenance of cognitive performance according to exercise intensity cannot be discussed without considering exercise duration. All these factors are closely-related and play a moderating role in acute exercise-cognition relationships. Dietrich and Audiffren suggest that more than the intensity, duration of exercise would be the predominant factor to account for the effect of exercise. Exercise duration is often suggested to negatively affect cognitive performance. The hypothesis is that when exercise duration lasts more than 1 h, the appearance of fatigue symptoms such as an increase in metabolic load and increased heat stress, the appearance of central and peripheral fatigue phenomenon, and several hormonal changes would lead to a decrement of cognitive processes efficacy. It is thus possible that our manipulation was not long enough to get any cognitive deficits. Even if pedaling 15–20 min at VT1 + 20% was certainly challenging for the participants, it is possible that cognitive deficits would have only occurred after this duration, just before the moment of exhaustion. Based upon our findings, we believe that exercise intensity indubitably play a crucial role in predicting cognitive performance during exercise because it shortens the time to exhaustion, however exercise intensity does not seem to be the main factor that alters cognition. The present study showed that cognitive performance was efficient despite very hard exercise intensity performed for 20 min, but the design of this study did not allow for an additional consideration of how long this efficiency could be maintained. Unfortunately, most studies have been conducted using a fixed duration and it is thus difficult to provide evidence relative to this suggestion at this time. To test this hypothesis, future studies should be conducted using exercise periods that run until exhaustion with a continuous monitoring of cognitive performance.

Note that, in Hüttermann and Memmert (2014) study, the fitness level of the athletes may co-vary with the information processing level linked to the specific demand of their team sport.
5. Conclusion

In conclusion, our study shows that selective response inhibition is facilitated throughout exercise, and that it is not deteriorated by exercise even when exercise is practiced at a very hard intensity. Although we discussed that a decline in cognitive control could still occur in other conditions of exercise (e.g., with lower fitness individuals or with longer exercise) the present results depict that cognitive control is a very robust cognitive function that is not significantly affected by exercise constraints.

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References