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Effect of Acute Exercise on Cognitive Control Required During an Eriksen Flanker Task

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This study aimed to determine how cognitive control, engaged in a task requiring selective inhibition, is affected by acute steady-state exercise. An adapted version of the Eriksen flanker task, involving three types of trials that varied according to their level of congruency (congruent trials, stimulus-incongruent trials, and response-incongruent trials) was performed during 2 periods of 20-min cycling at a carefully controlled intensity (50% of maximal aerobic power). The results indicated that moderate exercise improves reaction time (RT) performance on the Eriksen flanker task. This facilitating effect appeared to be neither dependent on the nature of the interference (stimulus level conflict vs. response level conflict) nor on the amount of cognitive control engaged in the task (congruent vs. incongruent trials). Distributional RT analyses did not highlight any sign of impairment in the efficiency of cognitive control.

Keywords: selective inhibition, reaction time, distributional reaction time analyses, stimulus level conflict, response level conflict

Currently, there is a consensus of opinion that moderate acute exercise enhances basic cognitive processes when both are performed simultaneously (for a review, see Tomporowski, 2003). Recent chronometric and electromyographic studies have suggested that most of this improvement is due to better efficiency of the peripheral motor processes (i.e., time interval elapsing from the onset of the response agonist muscle contraction to the mechanical response) and a smaller part is also due to a better efficiency of the peripheral sensorial processes (i.e., signal detection) (Davranche, Burle, Audiffren, & Hasbroucq, 2005, 2006). However, only a few studies have investigated the effect of acute exercise on higher cognitive functions while exercising, and at the moment results are somewhat equivocal. For example, Pesce, Capranica, Tessitore, and Figura (2003) and Pesce, Tessitore, Casella, Pirritano, and Capranica (2007) reported better reaction time

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(RT) performances during submaximal exercise on discriminative tasks requiring attentional orientation and cognitive flexibility. By contrast, Pontifex and Hillman (2007) found that moderate aerobic exercise reduced response accuracy for incongruent trials and decreased efficiency of the neuroelectric system during an Eriksen flanker task. The authors concluded that the attentional effort required during exercise may lead to inefficient allocation of neural resources, which leads to poorer interference control on the task. During Eriksen flanker tasks (Eriksen & Eriksen, 1974), a central target stimulus is presented simultaneously with two distractor stimuli (flankers) and participants are instructed to respond according to the target ignoring the flankers. Reaction time performance is usually reported to be better when relevant and irrelevant information correspond to the same response (congruent trial) than when they are mapped to different responses (incongruent trial). The RT lengthening observed during incompatible trials is attributed to the conflict between the activation of the incorrect response (mapped to the flankers) and the activation of the correct response (mapped to the target), which delays the response execution (interference effect).

Previous research examining the effect of exercise on the flanker task has tended to show no significant effect on RT (Hillman, Snook, & Jerome, 2003; Themanson & Hillman, 2006; Pontifex & Hillman, 2007). Although Kamijo, Nishihira, Higashiura, and Kuroiwa (2007) found a significant decrease in RT following exercise, Pontifex and Hillman (2007) showed increases in the number of errors during exercise at 60% maximum heart rate, probably revealing a speed–accuracy tradeoff (Pachella, 1974). However, the protocols of the previous studies make it difficult to confidently present directional hypotheses for RT in the current study because all of these studies, with the exception of Pontifex and Hillman, tested the effects following the cessation of exercise. Postexercise, the individual is in a different state of physiological arousal than during exercise (Åstrand, Rodahl, Dahl, & Stromme, 2003), which would affect the results. The present study aimed to further explore how acute moderate exercise affects cognitive control.

The use of an Eriksen flanker task gives the opportunity to disentangle stimulus-level interference from response-level interference. Because previous findings have shown that exercise operates for most part at motor and sensorial information–processing levels (Davranche et al., 2005, 2006a), we felt that it was useful to focus our attention independently at both extremes of the information-processing continuum. Therefore, a modified version of the flanker task previously used by Van Veen, Cohen, Botvinick, Stenger, and Carter (2001) and Hazeltine, Poldrack, and Gabrieli (2000) was carried out. This adapted version involved three types of trials, which varied according to their level of congruency: congruent trials (CO), stimulus-incongruent trials (SI), and response-incongruent trials (RI). During RI trials, the interfering effect results from a conflict occurring at both stimulus (early) and response (late) levels of processing. Thus, the stimulus conflict at an early processing level is confounded by the response conflict at the later processing level. On the contrary, during SI trials, there is only a conflict at an earlier processing level. Therefore, the stimuli used for CO and SI trials differ only in terms of visual interference, and the comparison of the respective RTs reflects stimulus conflict induced by the irrelevant flankers. Lastly, for SI and RI trials the visual interference is the same; thus, the comparison of the respective

RTs presumably provides information about response conflict. As a result, by disentangling the interference at both extremities of the information processing continuum, this experiment allowed examination of whether exercise interacts with a conflict occurring at the response level and/or with a conflict occurring at the stimulus level.

Because the conflict generated by RI trials (at both stimulus and response level) requires more cognitive control to overcome the interference effect than the conflict generated by SI trials (at stimulus level only), the design of this adapted Eriksen flanker task also provided the opportunity to assess the effect of exercise according to the amount of cognitive control engaged in the task. We made the assumption that if the effect of exercise depends on the amount of cognitive control implicated, we should observe an interaction between the exercise conditions and the types of trials. If exercise negatively affects cognitive control functions, we should expect that the deleterious effect will be even more pronounced when the amount of cognitive control engaged in the task is large.

Materials and Methods

Participants

Participants were students and staff members recruited in the local sport sciences university community through advertisement. All participants have moderately or highly active lifestyles in both their work and recreation. Before taking part in the experiment, participants (3 females and 11 males) signed written consent forms and were fully informed about the protocol. Participants completed a university health questionnaire. The local ethics committee approved the experiment.

Preliminary Protocols

The experiment began with a preliminary physiological test that was set up to individually determine the exercise workload of the following experimental sessions. The test, performed on a cycle ergometer (SRM, Germany), consisted of a continuous incremental protocol leading to volitional exhaustion. The pedal rate and heart rate were continuously recorded. After a 5-min warm-up at 75 W, the exercise workload increased 25 W every minute until exhaustion. Participants were verbally encouraged to achieve their maximal performance. During the last minutes of the test, 1-min collections of expired gases were collected in Douglas bags (Plysu Protection Systems Limited, Milton Keynes, U.K.). The expired fractions of oxygen (FEO_2) and carbon dioxide ($FECO_2$) were recorded using calibrated gas analyzers (Series 1400 gas analyzer, Servomex, Crowborough, U.K.), volumes were measured (Harvard dry gas meter, Harvard Apparatus Ltd., Edenbridge, U.K.), and volumes of oxygen (VO_2) were calculated. The power reached during the last 15 s of this test served to determine the individual exercise workload (50% of maximal aerobic power, MAP). Participants' anthropometrical and physiological characteristics are presented in Table 1.

Apparatus and Display. The participant sat on a cycle ergometer, fully adjustable for a perfect fit and equipped with a soft padding supports to comfortably

Table 1 Anthropometrical and Physiological Characteristics of Participants

	Mean ± *SD*		
Variables	**All**	**Female**	**Male**
Sample size	14	3	11
Age (years)	30 ± 8	31 ± 5	30 ± 9
Height (cm)	178 ± 6	170 ± 6	180 ± 4
Weight (kg)	75 ± 12	59 ± 9	80 ± 9
HR baseline (bpm)	66 ± 10	73 ± 5	64 ± 11
HR max (bpm)	182 ± 14	188 ± 9	180 ± 12
VO_{2max} (mL/kg/min)	45 ± 6	38 ± 1	47 ± 5
Workload (W)	152 ± 26	111 ± 20	163 ± 13
Workload (% HR_{max})	76 ± 6	81 ± 13	75 ± 3
Fitness categories[a]	3 ± 1	3 ± 1	3 ± 1

Note. SD = standard deviation; HR = heart rate; LT = lactate threshold; bpm = beats per minute. [a]The fitness categories were individually calculated according to Shvartz and Reibold (1990): 1 = excellent; 2 = very good; 3 = good; 4 = average; 5 = fair; 6 = poor; 7 = very poor.

support their arms, opposite a computer screen placed at 1 m in front of him or her. Two press buttons were fixed on the right and the left handles of the cycle's handlebar.

Design and Procedure. Before the experimental sessions, participants undertook a training session consisting of 8 blocks of 64 trials each to reach a stable level of RT performance and minimize potential learning effects. Following this, participants then completed two experimental sessions on separate days. One experimental session was performed while cycling at 50% of MAP on the ergometer and the other was performed at rest (sitting on the ergometer without cycling). The order of the experimental sessions was counterbalanced across participants. During each experimental session, the total amount of trials (512 trials) was divided into 8 blocks of 64 trials each: 4 blocks were performed during a first 15-min period and 4 further blocks during a second 15-min period. The two sets were separated by a 5-min resting period. The use of a 15-min period at 50% of MAP was based on previous studies that have successfully found a significant effect of exercise on cognitive function using this intensity and duration (Davranche, Burle, Audiffren, & Hasbroucq, 2005, 2006; Davranche & Audiffren, 2004). In addition, a 15-min exercise period seems to be a reasonable compromise to obtain a sufficient amount of data (approximately 250 trials), while avoiding fatigue. The exercise session was 10 min longer than the rest session owing to the 5-min warm-up period before each testing period. Heart rate was continuously recorded during both sessions and pedal rate self selected. The ergometer automatically adjusted the resistance of the electronic break as a function of the pedal rate to maintain a constant power output. As the freely chosen rate differs only slightly from the energetically best cadence (Brisswalter, Collardeau & Arcelin, 2002), self-selected pedaling rate allows the participant to reduce resource allocation to the physical movements inherent to cycling and so minimize dual task effects as compared with a fixed rate.

Participants were asked to respond as quickly and accurately as possible to a visual stimulus by pressing the appropriate key with the thumb. The stimulus corresponded to three colored circles, horizontally arranged, which were presented in a known location immediately after a 1-s fixation point. Participants had to respond according to the color of the central circle (the target), while ignoring the color of the flanker circles (the distractors), which were presented simultaneously for 1 s on both sides of the target. The visual angle between the target and flanker was 0.06°. The target colors red (R) and green (G) required a left-hand response, and the colors blue (B) and yellow (Y) required a right-hand response. As soon as a response key was pressed, the stimulus disappeared. When participants failed to respond within 1.5 s, the stimulus disappeared and the next trial began. The interval between the disappearance of the display and the onset of the next was 1.5 s. There were three types of trials: congruent trials (50%), stimulus-incongruent trials (25%), and response-incongruent trials (25%). In the congruent trials (CO), the target circle was flanked by circles that were identical to the target (e.g., RRR or BBB). In the incongruent trials (IN), the target circle was flanked by circles of a color that corresponded either to the same response assignment (e.g., GRG or YBY) or to the alternative response assignment (e.g., BRB or GYG). (Note that because there are four possible stimuli for CO and SI conditions but eight possible stimuli for RI condition, the frequency of occurrence of each possible stimulus is not the same in all the conditions. If the flankers were not identical to the target, but assigned to the same response, the trial corresponded to stimulus-incongruent trials (SI). If the flankers were assigned to the alternative response, the trial corresponded to response-incongruent trials (RI).

Data Analysis

The arcsine transformations of the error rate, the mean RT, and the delta plot analysis for RT were submitted to repeated-measures ANOVAs with exercise conditions and congruency as within-subject factors. Post hoc Newman-Keuls analyses were conducted on all significant interactions. Significance was set at $p < .05$ for all analyses. Effect sizes were calculated using partial eta square (η_p^2) for significant main effects.

To determinate whether the effects of exercise differ according to the nature of the conflict, we have independently assessed the conflict occurring at the stimulus level from the one occurring at the response level. Assuming that CO and SI trials differ only in terms of visual interference, we compared the RTs (SI minus CO) to assess the conflict occurring at the stimulus level. According to the same logic, considering that SI and RI trials differ only in terms of response conflict, we compared the RTs (RI minus SI) to assess the conflict occurring at the response level.

In addition, analyses of RT distributions were performed to explore the cognitive performance at a detailed level to obtain more information than can be achieved using standard statistical summary measures such as mean and variance (Davranche, Audiffren, & Denjean, 2006b). Therefore, the Vincent averaging, or Vincentization, technique was used (Jianq, Rouder, & Speckman, 2004; Ratcliff, 1979; Vincent, 1912). The distributions were binned in 10 classes (deciles), and the mean of each bin was computed. This was done for each subject separately. Graphic representations of the distributions were constructed using group RT distributions obtained by averaging individual RT distributions. The cumulative density function method has been used to represent RT distributions. For a given value (t) of RT along the x-axis, the cumulative density functions (CDFs) provide the probability of observing a RT value less than t value. From the Vincentized distributions, delta plots were estimated by plotting the difference between the values of the same bins of the rest and exercise conditions against the average of the same two values. The experiment has been designed to regroup both SI and RI trials under IN trials to allow the comparison between CO (50%) and IN (50%; SI 25% and RI 25%) trials classically used in the literature. Distribution analyses for CO and IN trials separately were thus performed to assess whether the interference effect size changed according to the length of RT. The dynamic of the delta plots is a relevant variable because the point of divergence between the delta plot curves indexes the level of inhibitory and the strength of inhibitory processes. A good metaphor is to compare the response inhibition with the physical action of pushing a brake pedal of a car. In the context of an emergency stop, the action is efficient when the driver is able to strongly and quickly push on the pedal, which corresponds to the level and the strength of the inhibition. When response inhibition is more efficient in one condition compared with another, we expected a more pronounced drop-off in the delta curve, which should be manifest earlier in time (i.e., at earlier decile corresponding to faster RTs; for details, see Ridderinkhof, 2002).

Repeated-measure ANOVA involving exercise, congruency, and deciles as within-subject factors was performed on Vincentized RT data. A set of ANOVAs was also conducted on the slopes, computed for the delta plot segments by connecting the data points of successive deciles (Deciles 1 and 2, Deciles 2 and 3, etc). These analyses involved exercise and decile as within-subjects factors to determine whether delta plots curves diverge between rest and exercise conditions.

Results

Response Accuracy

Accuracy was determined by percentage of decision errors. These data were analyzed using an ANOVA involving the condition (rest vs. exercise) and the type of trial (CO, SI, and RI). The ANOVA revealed no effect of exercise on error rate, $F(1, 13) = 2.18, p = .16, \eta_p^2 = .15$, but an effect of type of trial was found, $F(2, 26) = 23.14, p < .01, \eta_p^2 = .64$. Post hoc tests showed that the error rate for RI (12.4%) trials was higher than for both CO (7.5%, $p < .01$) trials and SI (6.3%, $p < .01$) trials. Accuracy, however, did not differ significantly between CO and SI trials ($p = .22$). There was no sign of interaction between the exercise condition and the type of trial ($F < 1$). Thus, the differences in RT performance observed through the manipulation of these two factors could not be explained by a speed–accuracy trade-off (Pachella, 1974).

Reaction Time

Reaction time performance was investigated with a repeated-measures ANOVA involving the condition (rest vs. exercise) and the type of trial (CO, SI, and RI). Results indicated that RT was shorter in the exercise (*M*: 409 ms, *SD*: 52 ms) compared with the rest (*M*: 431 ms, *SD*: 52 ms) condition, $F(1, 13) = 21.68$, $p < .01$, $\eta_p^2 = .63$. The results also confirmed that the flankers located in proximity to the target generated a conflict and lengthened RT, $F(2, 26) = 93.66$, $p < .01$, $\eta_p^2 = .88$. Post hoc tests showed that RT increased with the level of conflict. Reaction time for SI trials (*M*: 416 ms, *SD*: 52 ms) was longer than for CO trials (*M*: 406 ms, *SD*: 52 ms, $p < .01$), and RI trials (Mean: 438 ms, *SD*: 53 ms) elicited longer RTs than both SI ($p < .01$) and CO trials ($p < .01$) (Figure 1). There was no interaction between condition and congruency ($F < 1$).

Nature of the Conflict

An ANOVA examining the condition (rest vs. exercise) and the nature of the conflict (stimulus conflict vs. response conflict) was performed on RT. Results showed that the stimulus level conflict (SI – CO = +10 ms) was smaller than the response level conflict (RI – SI = +22 ms; $F(1, 13) = 7.99$, $p < .01$, $\eta_p^2 = .38$. Results also showed that there was no interaction between the exercise condition and the nature of the conflict ($F < 1$) (Figure 2).

Delta Plot Analysis for Reaction Time

An ANOVA examining exercise condition, congruence, and decile was conducted on Vincentized RT data (Figure 3A). We performed RT distribution analyses to assess whether exercise modified the interference effect size as a function of the response speed. The results showed a main effect of decile, which reflects an

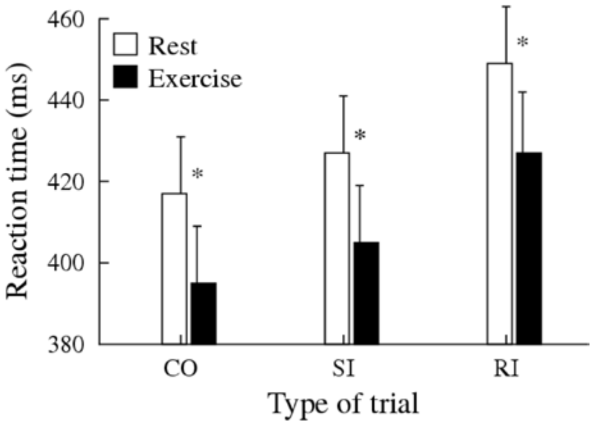

Figure 1 — Mean reaction time and standard error (ms) for each type of trial (CO: congruent; SI: stimulus incongruent; RI: response incongruent) during rest (empty bars) and exercise (full bars), *$p < .05$.

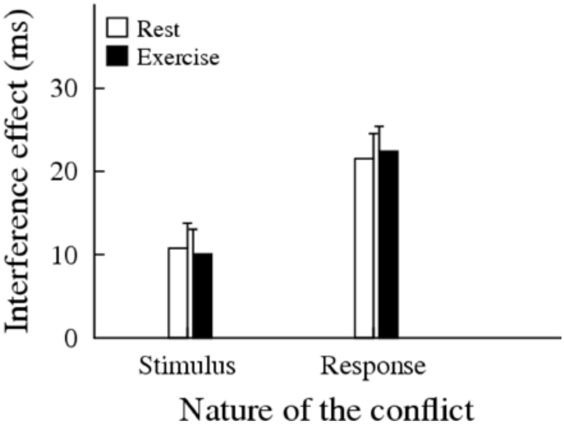

Figure 2 — Interference effect and standard error (ms) as a function of the nature of the conflict (stimulus vs. response level) during rest (empty bars) and exercise (full bars).

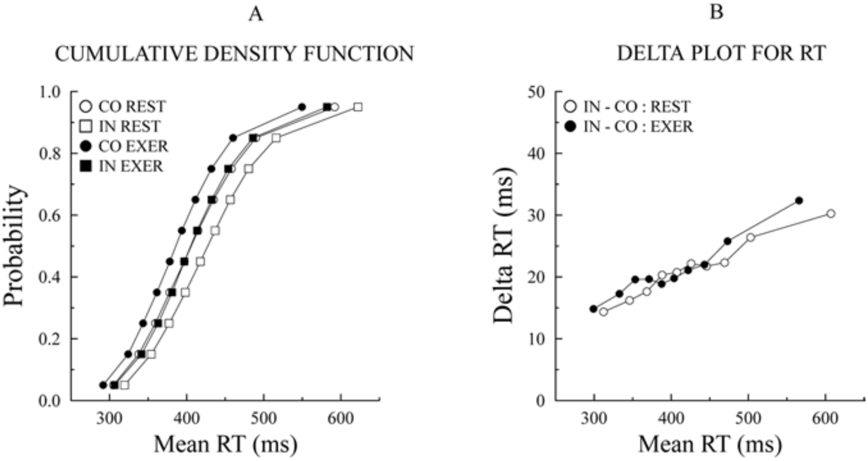

Figure 3 — (A) Cumulative density functions during rest (empty symbols) and exercise (full symbols) for congruent (CO, circles) and incongruent (IN, squares) trials. (B) Delta plot for interference effect generated by flanker stimuli as a function of increasing RT during rest (empty circles) and exercise (full circles) conditions.

increase in the magnitude of the interference effect as the RT lengthened, $F(9, 117) = 4.32$, $p < .001$, $\eta_p^2 = .25$. There was neither an effect of exercise condition nor an interaction between condition and deciles (*F*s < 1).

A second set of ANOVAs, which focused on the interference effect on the delta plot slopes, were conducted to examine whether it was possible to identify a point in time for which the delta plots curves diverge between exercise and rest. As suggested by the Figure 3B, results showed that the slopes did not significantly differ between conditions at any segment (*F*s < 1).

Discussion

In this study, we aimed to clarify the ways in which acute moderate exercise affects cognitive control, using an adapted Eriksen flanker task involving conflicts at both extremities of the information processing continuum and requiring a variable amount of cognitive control. Reaction time results clearly indicated that moderate exercise improves RT performance on the Eriksen flanker task. Despite the existence of an interference during certain trials (Figure 1) and whatever the nature of the conflict (Figure 2), moderate exercise enhanced performance by increasing response execution speed without changing accuracy.

The present study suggests that the effect of moderate exercise is beneficial for both congruent and incongruent conditions, and these findings are somewhat different from past research. Hillman and associates (Hillman, Snook & Jerome, 2003; Themanson & Hillman, 2006; Pontifex &Hillman, 2007) found no significant effect of moderate intensity exercise on performance of a flanker task as measured by the behavioral variable RT. However, it is difficult to compare the results of the current study with those of Hillman, Snook, and Jerome, and Themanson and Hillman, because the protocols were very different. In both of those studies: exercise intensity was very high, 30 min of treadmill running at >80% maximum heart rate, and subjects were tested following cessation of exercise. However, in the Pontifex and Hillman (2007) experiment, participants undertook the flanker task while cycling at 60% maximum heart rate, which is a moderate-intensity exercise comparable to the current study (76% maximum heart rate). Although RT was not affected by exercise (probably because of the occurrence of a speed–accuracy trade-off; Pachella, 1974), it should be noted that event-related potentials data suggest that exercise results in increased P2 amplitude, P3 amplitude and latency, and N2 latency and suggest a greater allocation of resources during stimulus encoding and longer cognitive processing speed. Despite the suspicion of a speed–accuracy trade-off, which makes the interpretation of the behavioral results problematic, a possible explanation for the differences in results is the fact that the adapted flanker task used in the Pontifex and Hillman study was different from that used in the current study. In the current study, colors were used as the relevant and irrelevant stimuli, whereas Pontifex and Hillman used arrowheads (i.e., < and >). More importantly, in the task using colored circles, four stimuli were matched to two responses, whereas the arrowhead task was a more conventional two-choice RT task and certainly less complex.

As expected, consistent with the results widely observed in the literature, the manipulation of distracting information postponed the response execution and reduced the response accuracy. During incongruent trials, the emergence of a conflict between the activation of the incorrect response and the activation of the correct response lengthened RT and generated more errors than during congruent trials. The present adapted Eriksen flanker task involved three types of trials that varied according to their level of congruency. Results showed that the postponement of the response execution is even longer when the conflict is elevated. However, there was no interaction between exercise and the type of trials, which suggests that the magnitude of the facilitating effect of exercise did not depend on the amount of cognitive control required to overcome the conflict. Moreover, delta plot curves (Figure 3B), which according to the activation suppression hypothesis (Ridderinkhof, 2002) can be interpreted as an index of cognitive control, appeared not to be affected during exercise. The positive effect of exercise observed during the present Eriksen task is consistent with previous results reported in the literature during basic cognitive tasks (for a review, see Tomporowski, 2003). This beneficial effect, unrelated to the cognitive control engaged to cope with the interference, could be explained by better efficiency of the peripheral motor processes during exercise (Davranche et al., 2005, 2006a). However, without electromyographic activity records, this assumption remains to be verified.

Davranche and collaborators (2005, 2006a) have shown that the major exercise-induced improvement in performance is related to greater efficiency of motor components due mostly to better synchronization of the motor unit discharge and at a lesser extent to a more efficient sensory processing. Accordingly, we expected that the influence of exercise would differ as a function of the nature of the conflict. To address this possibility, we set up an appropriate protocol to address whether the exercise interacts differently with a conflict occurring at the response level and with a conflict occurring at the stimulus level. However, present results do not highlight any difference according to the nature of the conflict, which suggests that the effect of exercise seems to be the same regardless of the locus of the interference.

Collectively, the present findings support the assumption that exercise does not influence cognitive control and suggest that exercise-induced arousal facilitates RT but does not interact with processing-specific conditions of the Eriksen flanker task. However, as stated by Coles and Tomporowski (2008), it is important to mention that the inconsistency among studies may be due to the multifaceted nature of higher-cognitive functions. Moreover, as suggested by Davranche and McMorris (2009), the contrasting findings also suggest that the effect of exercise may be more selective than general; thus, meticulous precautions must be taken to avoid precipitated generalization across different cognitive processes. Even though there is so far no explanation of the entire range of effects of acute exercise on cognitive functions, some cognitive processes appear to be impaired whereas others seem not to be altered or show, on the contrary, improvements (Davranche, 2008). As an example, recent studies (testing participants with similar characteristics) reported that exercise improves inhibitory online action control during a stop-signal task while cycling at moderate intensity (Joyce, 2008; Joyce, Graydon, McMorris, & Davranche, 2009), whereas Davranche and McMorris (2009) showed that the same type of exercise impairs the efficiency of selective response inhibition when it is necessary to choose the relevant rule to apply and to ignore a task-irrelevant dimension of a stimulus during a Simon task.

In summary, according to the activation suppression hypothesis (Ridderinkhof, 2002), the results of the current study suggest that the inhibition of the prepotent response generated by flanker stimuli is efficient during moderate exercise and appears not to be different from a rest condition. Currently, there is no theoretical argument to explain why cognitive processes are differently sensitive to the effects of exercise. Consequently, one issue for future research is clearly to further assess the specific rather than general effect of acute moderate exercise. Another interesting issue is also to assess whether some interindividual characteristics could explain the discrepancy of some results—especially the fitness level, the habit of being exposed to physical stress, and the motivation to achieve good performances.

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