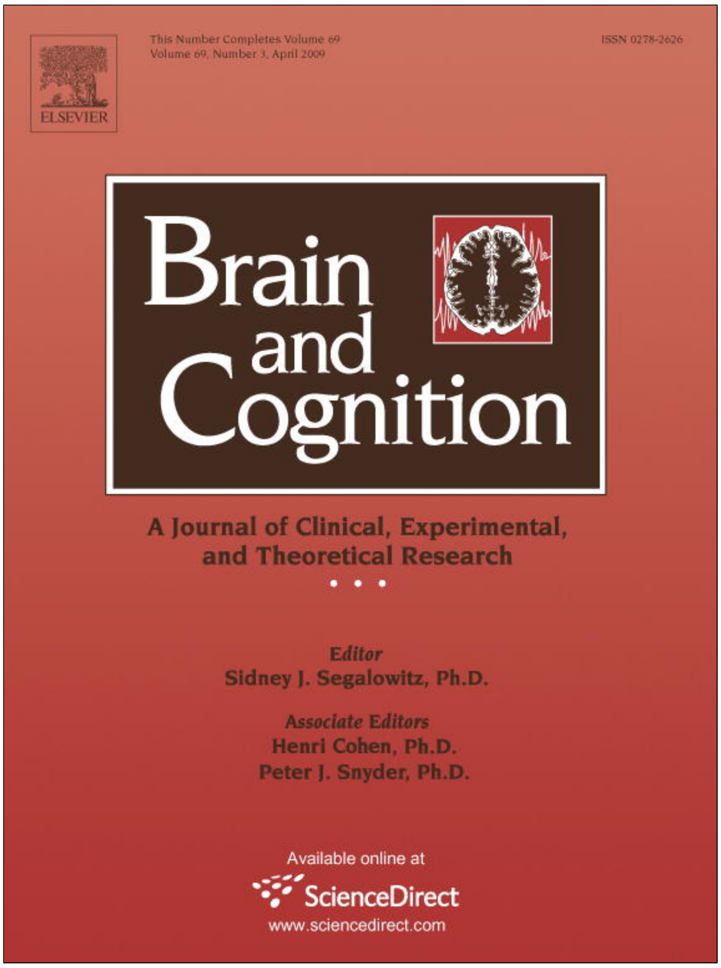
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Specific effects of acute moderate exercise on cognitive control

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ABSTRACT

The main issue of this study was to determine whether cognitive control is affected by acute moderate exercise. Twelve participants [4 females ($VO_{2\ max}$ = 42 ml/kg/min) and 8 males ($VO_{2\ max}$ = 48 ml/kg/min)] performed a Simon task while cycling at a carefully controlled workload intensity corresponding to their individual ventilatory threshold. The distribution-analytical technique and the delta plot analysis [Ridderinkhof, K. R. (2002). Activation and suppression in conflict tasks: Empirical clarification through distributional analyses. In W. Prinz & B. Hommel (Eds.), *Common mechanisms in perception and action. Attention and performance* (Vol. 19, pp. 494–519). Oxford: Oxford University Press.] were used to assess the role of selective response inhibition in resolving response conflict. Results showed that cognitive processes appeared to be differently affected by acute moderate exercise. Reaction time results confirmed that performance is better (faster without change in accuracy) when the cognitive task is performed simultaneously with exercise. Between-trial adjustments (post-conflict and post-error) highlighted that cognitive control adjustments are also fully efficient during exercise. However, the effect of congruency (Simon effect) appeared to be more pronounced during exercise compared to rest which suggests that the response inhibition is deteriorated during exercise. The present findings suggest that acute moderate exercise differently affects some specific aspects of cognitive functions.

1. Introduction

In sport and exercise activities, successful performances strongly depend on the ability to simultaneously carry out cognitive and physical demands. It has been established that acute moderate exercise enhances cognitive functions (e.g., Chmura, Krysztofiak, Ziemba, Nazar, & Kaciuba-Uścilko, 1998; Davranche & Audiffren, 2004; McMorris & Graydon, 1996; Yagi, Coburn, Estes, & Arruda, 1999). Davranche, Burle, Audiffren, and Hasbroucq (2005, 2006) also showed that most of this improvement is due to better efficiency of the peripheral motor processes (i.e., better synchronisation of the motor units discharge), and a smaller part is due to greater efficiency of the peripheral sensorial processes. However, even if the effect of exercise on basic cognitive processes is now well documented (for reviews see McMorris & Graydon, 2000; Tomporowski, 2003), the effect of acute exercise on higher-cognitive processes such as cognitive control, working memory and cognitive flexibility is still very much a matter of debate.

1.1. Cognitive control during exercise

Only few studies have assessed the effect of acute exercise on higher-cognitive functions. For instance, Pesce, Capranica, Tessitore, and Figura (2002) and Pesce, Tessitore, Casella, and Capranica (2007) found an improvement in performances during discriminative reaction time (RT) experiments requiring attentional orientation and cognitive flexibility. Alternatively, Pontifex and Hillman (2007) failed to observe any change in cognitive control using an Eriksen flanker task during which distracting information enter into competition with target information. Dietrich and Sparling (2004) were the first to highlight a selective impairment on prefrontal-dependent cognitive tasks during exercise on tasks requiring different amounts of cognitive control. These authors suggested that the transient hypofrontality hypothesis proposed by Dietrich (2003) could explain the decline observed during acute exercise. The transient hypofrontality hypothesis suggests that during exercise there is a massive and sustained activation of motor and sensory systems. Accordingly, a reallocation of the limited availability of information processing resources is necessary and leads to a temporary inhibition of neural networks (e.g., areas of the frontal lobe involved in higher-cognitive functions) that have not been prioritized. Thus, processes related to the inhibited regions of the brain are expected to manifest impairment during exercise (for details see Dietrich, 2006). However, the sporadic results as well as

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the disparate findings in the current literature do not allow clarification of the effect of acute exercise on cognitive control and executive functions. Moreover, the diversity of the protocols also lead to many equivocal results, and considerable differences in experimental protocols (e.g., exercise intensity and duration, time on task, nature of the cognitive task) do not facilitate the synthesis and the comparison of results.

The main issue of this study was to determine whether acute moderate exercise affects cognitive control in an interference task (Simon task) while cycling at a carefully controlled workload intensity. The distribution-analytical technique and the delta plot analysis (Ridderinkhof, 2002; Ridderinkhof, van den Wildenberg, Wijnen, & Burle, 2004) were used to assess the role of selective response inhibition in resolving response conflict.

1.2. Conflict resolution

In the Simon task, participants had to select the task-relevant feature of a stimulus (the colour) and inhibit the surrounding task-irrelevant feature (the spatial location) of the same stimulus. The relevant and irrelevant information are integral parts of the same stimulus and participants had to choose the appropriate rule to apply rather than the relevant information to use. There were two types of trials: the congruent trials (CO) 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 incongruent trials (IN) in which the spatial location of the stimulus corresponded to the opposite spatial location of the response (e.g., left stimulus/right response). During such interfering tasks, RT performance is usually reported to be shorter when relevant and irrelevant information correspond to the same response than when they are mapped to different responses. This RT lengthening observed during incompatible trials 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.

An additional purpose of this study was to determine, whether the proficiency of selective response inhibition mainly solicited during the Simon task is affected by exercise. To this aim, the distribution-analytical technique and the delta plot analysis (Ridderinkhof, 2002; Ridderinkhof et al., 2004) were used to assess the role of selective response inhibition in resolving response conflict. More precisely, the delta plots were constructed by plotting the congruency effect as a function of the response speed. According to the activation suppression hypothesis (Ridderinkhof, 2002), the build up of selective response inhibition during the conflict task results in a reduction of the congruency effect for slow responses compared to fast responses. Hence, the delta plot curve, which indexes an online inhibitory control, was used to assess the selective inhibition of the automatic response activated on the basis of the distracting information. The delta plot technique has already been successfully applied to the examination of the effects of alcohol (Ridderinkhof et al., 2002), methylphenidate, attention deficit hyperactivity disorder (Ridderinkhof, Scheres, Oosterlaan, & Sergeant, 2005), and mild cognitive impairment (Wylie, Ridderinkhof, Eckerle, & Manning, 2007) on the efficiency of response inhibition in conflict tasks. If the efficiency of selective response inhibition is modified by exercise, the magnitude of interference effects as a function of response speed should be different and we should observe diverging delta plot curves between rest and exercise conditions.

1.3. Conflict adaptation

During conflict tasks, subjects actively monitor their performances and adjust the cognitive control during the task. The interference effect and the control engaged to cope with a conflict depend on the congruency of the preceding trial (Gratton, Coles, & Donchin, 1992; Kerns et al., 2004). The interference effect generated by the irrelevant information is actually weaker after incongruent trials than after congruent trials. Such between trial adjustments of control result from the occurrence of a high conflict on incongruent trials which leads to the engagement of greater cognitive control and, as a result, reduces the influence of the irrelevant information on the subsequent trial. Thus, classically RTs on incongruent trials preceded by incongruent trials (<<IN) are faster than RTs on incompatible trials preceded by compatible trials (<<CO). One explanation for these trial-to-trial adjustments is the conflict-monitoring hypothesis proposed by Botvinick, Braver, Barch, Carter, and Cohen (2001) and also supported by several brain imaging studies (Kerns, 2006; Kerns et al., 2004). This hypothesis states that conflict adjustments are associated with anterior cingulated cortex (ACC) and prefrontal (PFC) brain areas. The ACC conflict-monitoring serves as a signal that contributes to the subsequent recruitment of the PFC in order to minimise the conflict. Another behavioural phenomenon also reflecting a cognitive control adjustment is the fact that, following an error, participants adopt a more conservative strategy in order to prevent more errors. Therefore, RTs are slower immediately after an error than after a correct response. In comparison to other conflict tasks (Eriksen flanker task, Stroop task), previous research has shown that the Simon task produce the most robust cognitive control adjustments (Sturmer, Leuthold, Soetens, Schroter, & Sommer, 2002). Thus, the last objective of the present study was to determine whether sequential behavioural adjustments (between trials post-conflict and post-error adjustments) are modified by exercise, by assessing the dynamics of cognitive control according to the nature of the preceding trials during the Simon task.

2. Materials and methods

2.1. Participants

Participants were recruited in the local sport sciences university community through advertisement. Participants were undergraduate, postgraduate students and staff members with a moderate, activate or highly active level of activity in both their work and recreation. Participants had no noteworthy cycling history. Before taking part in the experiment, all participants (4 females and 8 males) signed written consent forms and were fully informed about the protocol. The University health questionnaire has been given to all participants. Experiment was approved by local ethics committee.

2.2. Preliminary protocols

The experiment began with preliminary physiological tests, which served to individually determine the exercise workload of the subsequent experimental sessions. The first test was a continuous incremental protocol until volitional exhaustion on a cycle ergometer (Lode Excalibur, Netherlands). After a 5-min warm-up at 75 W, the workload progressively increased until exhaustion (25 W/min for males and 15 W/min for females). The pedal rate and heart rate were continuously recorded and participants were verbally encouraged to achieve their maximal level. During the last minutes of the test, 1-min collections of expired gases were collected in Douglas bags (Plysu Protection Systems Limited, Milton Keynes, UK). The expired fractions of oxygen (FEO_2) and carbon dioxide ($FECO_2$) were recorded using calibrated gas analysers (Series 1400 gas analyser, Servomex, Crowborough, UK), volumes were measured (Harvard dry gas meter, Harvard Apparatus Ltd., Edenbridge, UK) and volumes of oxygen (VO_2) were calculated. The maximal blood lactate concentration was also measured at the end of the test through a sample of blood withdrawn using a needle pricked in the finger (YSI 2300 Stat Plus, Yellow Springs Instruments Co. Inc., Yellow Springs, USA).

The maximal aerobic power (MAP) reached during the last 15 s of this maximal effort test served to estimate the intensity of a second physiological test performed to calculate the individual's lactate threshold power (LTP). The lactate threshold test consisted in successive 5-min stages on a cycle ergometer, increased by 15 W for males and by 10 W for females until exhaustion. At the end of each 5-min stage, the oxygen consumption was calculated during the last minute and the blood lactate concentration was measured. Participants' anthropometrical and physiological characteristics are presented in Table 1.

2.3. Apparatus and display

The participant sat on a cycle ergometer (Lode Excalibur, Netherlands), equipped with a soft padding supports to comfortably support their arms, face to a computer screen placed at 1 m in front of him/her. The position of the ergometer was fully adjustable for a perfect fit. Two response keys were fixed on the right and the left handles of the cycle's handlebar. Every participant was tested in an environmental chamber with a temperature of 19 °C and a relative humidity of 60%.

2.4. Design and procedure

At the beginning of the experimental session, participants practiced a training session consisting of 4 blocks of 64 trials to reach a stable level of RT performance and minimise potential learning effects. Then, participants were required to complete two sets of 5 blocks of reaction time (5 blocks performed at rest and 5 blocks while cycling). The two sets were separated by a 15-min resting period and the order was counterbalanced across participants.

The exercise set consisted in 5 blocks of 100 trials performed while cycling at the LTP on a cycle ergometer (Lode Excalibur, Netherlands). The total cycling time was about 21 min and the cognitive task began at the end of the 3-min progressive incremented warm-up period. The five blocks were successively administrated and subjects were asked to keep cycling during the transition between blocks (from 15 to 30 s). The first block of the set was considered as dual-task practice and was discarded from the statistical analyses. Heart rate was continuously recorded and pedalling rate was freely chosen (the ergometer automatically adjusted the resistance of the electronic break as a function of the pedal rate in order to maintain a constant power output). The same procedure was followed for the rest set with the exception that participant was seated on the cycle ergometer without cycling. Note that, despite that the cognitive test lasted about 18 min in both conditions, the rest set was slightly shorter than the exercise set due to the absence of 3-min warm-up period.

Table 1
Anthropometrical and physiological characteristics of participants.

Variables	Mean ± SD		
	All	Female	Male
Sample size	12	4	8
Age (years)	32 ± 9	32 ± 10	32 ± 8
Height (cm)	176 ± 10	165 ± 2	181 ± 7
Weight (kg)	73 ± 13	59 ± 6	80 ± 9
HR baseline (bpm)	74 ± 13	81 ± 19	70 ± 10
HR max (bpm)	185 ± 10	189 ± 6	183 ± 12
Blood lactate max (mmol/l)	9 ± 1	10 ± 1	9 ± 1
$VO_{2\ max}$ (ml/kg/min)	46 ± 6	42 ± 8	48 ± 4
LT power (W)	149 ± 45	102 ± 28	172 ± 31
LT power (% HR_{max})	77 ± 4	75 ± 6	77 ± 4
*Fitness categories**			
Shvartz and Reibold (1990)	3 ± 1	3 ± 1	3 ± 1
Brooks, Fahey and White (1996)		High	Very high

Note: SD = standard deviation; HR = heart rate; LT = lactate threshold.
* The participant's fitness was individually calculated according to the categorisation of Shvartz and Reibold (1990): 1 = excellent; 2 = very good; 3 = good; 4 = average; 5 = fair; 6 = poor; 7 = very poor; and according to the categorisation of Brooks et al. (1996).

2.5. Cognitive task

Participants were asked to respond, as quickly and accurately as possible, by pressing the appropriate key with the right or the left thumbs according to the colour of a circle delivered either to the left or to the right of a fixation point. Participants had to respond according to the task-relevant aspect of the stimulus (the colour) and to ignore the task-irrelevant aspect of the stimulus (the location). There were two types of trials in each block: congruent trials (50%) and incongruent trials (50%). In the congruent trials (CO), the spatial location of the stimulus corresponded to the task-relevant aspect of the stimulus. The spatial location of the stimulus corresponded to the spatial location of the response. On the contrary, for incongruent trials (IN), the spatial location of the stimulus did not correspond to the task-relevant aspect of the stimulus. The spatial location of the stimulus corresponded to the opposite spatial location of the response. Each trial began with the presentation of a cross, corresponding to a fixation point, which stayed on throughout the trial. After 1 s, one of the two stimuli was presented and the participant had to respond according to the task-relevant aspect of the stimulus by a left press when the circle was red and by a right press when the circle was green. Whatever the correctness, the delivery of the response turned off the stimulus. When participants failed to respond within 1.5 s, the stimulus turned off and the next trial began. The ISI was 500 ms.

2.6. Data analysis

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

In addition, distribution analyses were performed on mean RT in order to explore the cognitive performance at a more fine-grained level and to obtain more information than can be achieved using standard statistical summary measures like mean and variance. In each exercise condition, RT-distributions (for CO and IN trials separately) were obtained using individual RT-distributions "Vincentized" (Ratcliff, 1979) into 10 equal-size speed bins (deciles). The data presented are the mean values of each set averaged across participants. Delta plots were then constructed by plotting congruency effect size (IN minus CO) as function of the response speed (average of means RTs in the CO and IN conditions per decile). Repeated-measure ANOVA involving exercise, congruency and deciles as within-subject factors were performed on RT-distributions to determine whether delta plots curves diverge between rest and exercise conditions. Slopes were computed for the delta plot segments by connecting the data points of decile 1 and 2, decile 2 and 3, decile 3 and 4, decile 4 and 5, decile 5 and 6, decile 6 and 7, decile 7 and 8, decile 8 and 9 and decile 9 and 10. A set of ANOVAs was conducted on these slopes included the within-subjects factors exercise and decile.

3. Results

3.1. Response accuracy

Accuracy was determinate in percentage of decision errors. These data were analysed using an ANOVA involving the condition (rest vs exercise) and the congruency (congruent vs incongruent). The analyse showed that there was no effect of exercise on decision error rate ($F(1,11) = 2.45$, $p = .15$, $\eta_p^2 = .18$), and no interaction between condition and congruency ($F < 1$). Only the main effect of congruency was significant ($F(1,11) = 15.60$, $p < .01$, $\eta_p^2 = .59$) with a higher error rate for IN trials (10.3%) than for CO trials (4.1%).

3.2. Reaction time

An ANOVA involving the condition (rest vs exercise) and congruency (congruent vs incongruent) performed on mean RT highlighted a main effect of exercise condition ($F(1,11) = 13.24$, $p < .01$, $\eta_p^2 = .55$) and a main effect of congruency ($F(1,11) = 31.03$, $p < .01$, $\eta_p^2 = .74$) but these were superseded by a two-way interaction between exercise condition and congruency ($F(1,11) = 6.27$, $p < .05$, $\eta_p^2 = .36$; Fig. 1).

Table 2 shows the mean RT, standard deviation and effect size for congruent and incongruent trials at rest and during exercise. Newman-Keuls post-hoc analyse showed that RT was significantly slower in the incongruent trials than in the congruent trials in both exercise conditions, and that RT was significantly slower at rest than during exercise at either congruency levels. Thus, the interaction demonstrated that the Simon effect (IN minus CO) is significantly more pronounced during exercise (+39 ms) than at rest (+31 ms).

3.3. Sequential behavioural effects

3.3.1. Post-conflict adjustments

An ANOVA involving the condition (rest vs exercise), the compatibility on trial n (CO vs IN) and the compatibility on trial $n - 1$ (CO vs IN) was performed on mean RT. Results did not highlight a significant second-order interaction between these three factors ($F < 1$) which suggests that the between-trial post-conflict adjustment was not affected by moderate exercise during the Simon task. As suggest by Fig. 2, whatever the exercise condition, the Simon effect was smaller when the preceding trial is incongruent compared to when the preceding trial is congruent (rest: $F(1,11) = 22.05$, $p < .01$, $\eta_p^2 = .67$; exercise: $F(1,11) = 61.89$, $p < .01$, $\eta_p^2 = .85$).

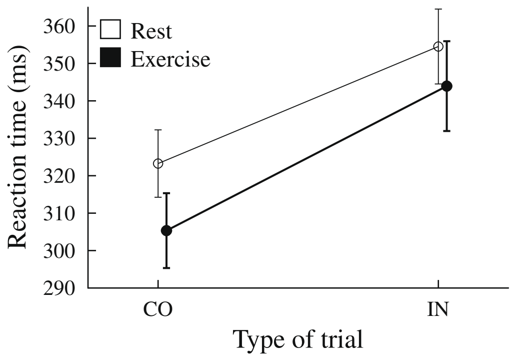

Fig. 1. Mean reaction time and standard error in millisecond for CO (congruent) and IN (incongruent) trials during rest (empty circles) and exercise (full circles) conditions.

Table 2
Mean reaction times (RT in ms) and standard deviation (SD) per exercise condition (rest and exercise) and congruency (congruent and incongruent) in the Simon task.

Exercise condition	Signal–response congruency				
	Congruent		Incongruent		Effect size
	Mean RT	SD	Mean RT	SD	
Rest	323	32	355	36	31
Exercise	305	33	344	42	39
Effect size	18		11		

3.3.2. Post error adjustments

An ANOVA involving the condition (rest vs exercise) and the correctness of the preceding trial (correct vs error) was performed to assess whether between-trial RT post-error adjustment was affected by moderate exercise during the Simon task. Results revealed only a main effect of exercise condition ($F(1,11) = 13.53$, $p < .01$, $\eta_p^2 = .55$) and a main effect of the correctness of the preceding trial ($F(1,11) = 16.43$, $p < .01$, $\eta_p^2 = .60$). The interaction between the condition and the correctness of the preceding trial was not significant ($F < 1$). This finding suggests that the RT slowing observed immediately after an error is the same whatever the exercise condition (Fig. 3).

3.3.3. Delta plot analysis for reaction time

An ANOVA involving condition (rest vs exercise) and decile was conducted on the individual delta plots. As suggested by Fig. 4B, the ANOVA confirmed that the interaction between exercise condition and decile was significant ($F(9,99) = 2$, $p < .05$, $\eta_p^2 = .15$). Newman-Keuls analyses showed a significant levelling off in the rest

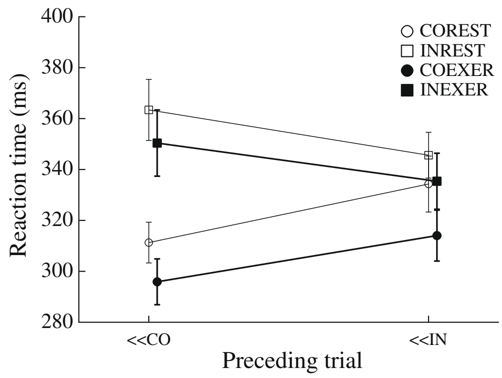

Fig. 2. Mean reaction time and standard error in millisecond during rest (thin) and exercise (thick) conditions for congruent (CO, cross) and incongruent (IN, square) trials according to the compatibility of the preceding trial $n - 1$ ($\ll$ CO: congruent; $\ll$ IN: incongruent).

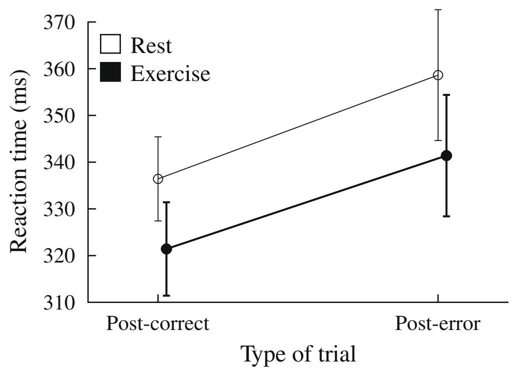

Fig. 3. Reaction time and standard error in millisecond according to the correctness of the preceding trial during rest (empty circles) and exercise (full circles).

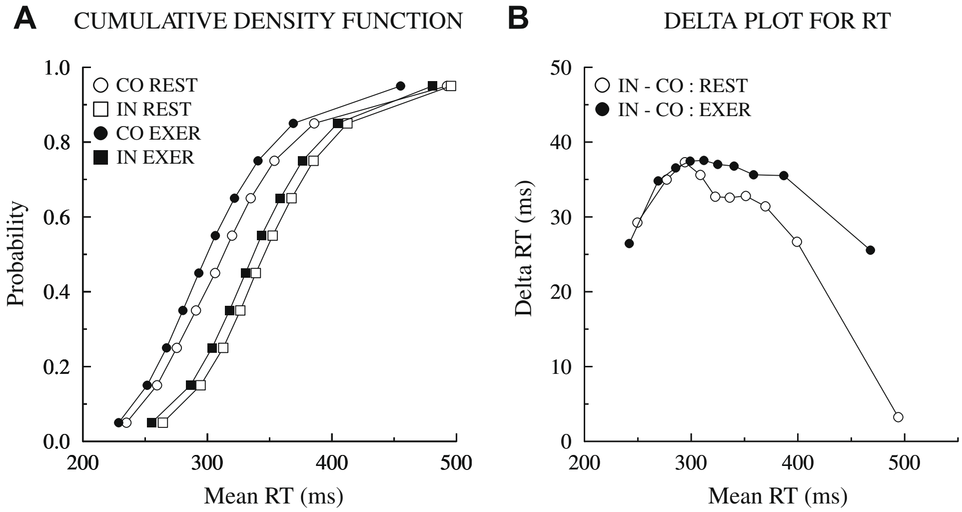

Fig. 4. (A) Cumulative density functions during rest (empty symbols) and exercise (full symbols) for congruent (CO, circles) and incongruent (IN, squares) trials. (B) Delta plot for congruency effect generated by task-irrelevant information as a function of increasing RT during rest (empty circles) and exercise (full circles) conditions.

condition between the fastest decile (1st decile) and the slowest decile (10th decile) ($p < .01$). By contrast, any significant drop off was observed in the exercise condition.

A second set of ANOVAs, focused on the effect of exercise on the delta plot slopes, were conducted to determine whether delta plot curves differ between conditions. Results showed that the slopes diverged, according to the exercise condition, at the 4th segment of the delta plot (d4-5: $F(1,11) = 15.45$, $p < .005$, $\eta_p^2 = .58$). The slopes did not differed significantly at any other segment of the delta plots (d1-2: $F < 1$; d2-3: $F < 1$; d3-4: $F(1,11) = 2.56$, $p = .14$, $\eta_p^2 = .19$; d5-6: $F < 1$; d6-7: $F < 1$; d7-8: $F < 1$; d8-9: $F(1,11) = 1.76$, $p = .21$, $\eta_p^2 = .14$; d9-d10: $F(1,11) = 1.54$, $p = .24$, $\eta_p^2 = .12$). The dissociation of delta plot slopes between conditions observed at the 4th segment is interpreted as a difference in terms of inhibition efficiency and suggests a weaker inhibitory control during exercise compared to rest.

Together, these findings highlighted that the levelling off and the turning negative of the delta plot, which both reflect an online act of inhibitory control, were less prominent in the exercise condition compared to the rest condition.

4. Discussion

The main aim of this study was to clarify how cognitive control functions are affected by acute moderate exercise. To this aim a Simon task was performed during a 20-min steady state cycling exercise at ventilatory threshold intensity.

As expected, the manipulation of irrelevant information during the Simon task lengthens the RT and increases the number of errors. The RT lengthening as well as the decrease in accuracy, observed in incongruent trials, is generated by the emergence of a conflict. In fact, the conflict between the activation of the incorrect response (associated with the task-unrelated aspect of the stimulus) and the activation of the correct response (associated with the task-related aspects of the stimulus) delays the response execution. Reaction time results also confirmed that performances are better (faster without change in accuracy) when the cognitive task is performed simultaneously with a moderate exercise. This beneficial effect, widely observed in the literature, is consistent with previous results and could easily be explained by better efficiency of the peripheral motor processes during exercise (Davranche et al., 2005, 2006).

4.1. Post-conflict and post-error adjustments

The between-trial monitoring capacity has been assessed to determine if strategic adjustments following conflict and following error are affected by exercise. As predicted, trial-to-trial analyses at rest showed that during the Simon task the occurrence of a conflict and the subsequent engagement of control depend on the congruency of the preceding trial. The congruency effect is less when the preceding trial is incongruent ($\ll$ IN) compared to when the preceding trial is congruent ($\ll$ CO). Following incongruent trials, post-conflict adjustments typically lead to faster RT performance on incongruent trials but to slower RT performance on congruent trials. Such post-conflict adjustments have been observed in the same way during exercise and there is no sign of any impairment of this action monitoring process. Moreover, the trial-to-trial analyses of post-error responses slowing usually observed immediately following errors revealed that, similarly to the rest condition, a top-down cognitive control is implemented during exercise to increase accuracy and prevent error. In sum, both between-trial adjustments (post-conflict and post-error) suggest that cognitive control adjustments are fully efficient during a steady state moderate exercise. Participants appear to actively monitor their performances during exercise and seem to be able to correctly adjust the cognitive control during the task. This is consistent with recent results of Themanson and Hillman (2006) which reported a fully efficient action monitoring during an Eriksen task performed following a 30-min acute treadmill exercise in higher-fit individuals. However, as suggested by these authors, the efficiency of the action monitoring seems to be function of participant's cardio-respiratory fitness and further research is necessary to precise the relationship between fitness level and top-down cognitive control efficiency.

4.2. Selective Inhibition

Contrary to the beneficial results reported above, the Simon effect (+39 ms) observed during exercise is more pronounced than at rest (+31 ms) and this finding suggest that moderate exercise impairs the ability to selectively inhibit the automatic response generated by distracting information related to a task-irrelevant aspect of the stimulus.

In addition, the delta plot technique highlights that this impairment can be attributed, at least in part, to a deficient response inhibition revealed during exercise. Indeed, the delta plot analyses performed on the Simon effects indicated that the levelling off of the delta plots is less pronounced and is manifest later during exercise compared to rest. According to the activation–suppression model of Ridderinkhof (2002), when response inhibition is proficient, we see a pronounced levelling off of the delta plot (reflecting a reduction of the interference effect for slower responses). Thus, the present finding indicates that 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.

4.3. Specific rather than general effect

Collectively, the present findings are complex because the outcomes of this experiment clearly suggest that cognitive processes are differently sensitive to the effect of exercise. Some cognitive functions are impaired (i.e., selective inhibition, response inhibition), whereas others are not altered and show on the contrary the full efficiency (i.e., top-down cognitive control, RT performance). As a consequence, even if some results highlight an impairment of some cognitive functions during exercise (e.g., Dietrich & Sparling, 2004), this effect of exercise appears to be specific rather than general and 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).

Additionally, it is important to note that some effects are not accessible through the unique measure of the mean RT. In the present study, RT results showed that the performances are better when the cognitive task is performed during exercise and this positive effect is probably due to better efficiency of the peripheral motor processes. Hence, provided that the cognitive task requires a motor response, we can imagine that this massive effect should consistently conceal other less obvious effects like the deficient response inhibition observed during the Simon task. Thus, it seems to be prudent to use additional variables and specific analyses, like the delta plot analyses or the fractionated RT, as often as possible in order to assess well-defined cognitive functions.

Consequently, one issue for future research is to consider whether the beneficial effect of exercise may be limited to motor response tasks. Future investigations are needed to determine whether the beneficial effect of exercise could be observed during cognitive tasks which do not require motor components and during cognitive tasks not performed under time pressure.

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