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A distributional analysis of the effect of physical exercise on a choice reaction time task

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Abstract
The aim of this study was to examine the facilitating effects of physical exercise on the reaction process. Eleven participants with specific expertise in decision-making sports performed a choice reaction time task during moderate sub-maximal exercise (90% of their ventilatory threshold power). Participants were tested at rest and while cycling. During exercise, the participants were faster, without being more variable. We suggest that the effect of exercise on cognitive performance was due to a major generalized improvement of the whole distribution of response time and, although the benefit effect was small, it was consistent throughout the entire range of reaction times.

Keywords: *Reaction time distributions, time on task, information processing, sub-maximal exercise, energetic factor, facilitating effect*

Introduction

The effects of physical exercise on response performance have been studied using a wide variety of information-processing tasks (for comprehensive reviews, see McMorris & Graydon, 2000; Tomporowski, 2003). A facilitating effect of exercise has been widely observed on cognitive performance during sub-maximal exercise (Arcelin, Brisswalter, & Delignières, 1997; Arcelin, Delignières, & Brisswalter, 1998; Brisswalter, Legros, & Delignières, 1994; Chmura, Krysztofiak, Ziemba, Nazar, & Kaciuba-Uscilko, 1998; Davranche & Audiffren, 2004; Delignières, Brisswalter, & Legros, 1994; McMorris & Graydon, 1996, 1997; Paas & Adam, 1991; Yagi, Coburn, Estes, & Arruda, 1999). This improvement is generally explained by increased arousal due to an elevation of the cortical concentration of catecholamines. In line with this hypothesis, Chmura, Nazar and Kaciuba-Uscilko (1994) and Chmura *et al.* (1998) observed a correlation between plasma catecholamine concentration and reaction time during exercise. These authors claimed that increases in concentrations of central nervous system catecholamines during exercise should result in speeded performance. It has been suggested that the adrenaline threshold (defined as a sudden increase in blood adrenaline concentration with exercise intensity) could be associated with improvements in cognitive performance (Chmura *et al.*, 1994, 1998). However, previous studies using different experimental protocols have shown that improvements in cognitive performance elicited by exercise were generally observed between 40% and 60% of maximal oxygen uptake ($\dot{V}O_{2max}$) (e.g. Brisswalter *et al.*, 1994; Delignières *et al.*, 1994; Paas & Adam, 1991). This metabolic load, located under ventilatory threshold power, mainly solicited aerobic metabolism without blood acidosis or accumulation of metabolic waste. In this study, we chose an exercise intensity below the VTP with the aim of observing an improvement in reaction time performance without any drift of the cardiorespiratory parameters. Although this might seem at odds with the proposal of Chmura *et al.* (1994, 1998), it was necessary if we were to interpret our results in terms of time on task. If a drift of the respiratory parameters was observed, it would be difficult to interpret the results because the effects resulting from this drift would merge with the effects induced by the time spent on task.

In a previous study, the facilitating effects of physical exercise were reflected in the appearance of boredom effects during the reaction time task (Davranche & Audiffren, 2004). Thus the over-stimulation

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induced by exercise appears to counteract a decrement of performance rather than raise performance under optimal conditions. Similar patterns of results were observed following amphetamine (Sanders, 1983) and nicotine (Davranche & Audiffren, 2002) administration, suggesting that the facilitating effects of psychotropic drugs were better observed when participants performed cognitive tasks under sub-optimal experimental conditions (i.e. sleep loss or boredom conditions). In addition, this pattern of results could be interpreted as reflecting the energetic involvement of amphetamines, nicotine and physical exercise. However, further research is necessary to verify the energetic involvement assumption as regards the effects of physical exercise. Moreover, previous studies based on mean reaction times and the additive factors method (AFM; Sternberg, 1969, 1998) suggested that physical exercise spares the stages of stimulus identification, response selection and motor adjustment (Arcelin *et al.*, 1998; Davranche & Audiffren, 2004). Indeed, the use of complementary approaches (e.g. electromyographic activity, reaction time and motor time distributions, electrophysiological indices to the AFM) is necessary to explore factor effects on cognitive performance. The effects of physical exercise on mental processing have typically been studied using the reaction time paradigm and inferences based on mean reaction time (RT). To our knowledge, no RT-distribution analyses have been used to investigate the effect of physical exercise on information processing. However, more information is potentially available using a procedure based on the entire distribution function. The aim of this experiment was to use RT-distribution analyses to assess and characterize the effects of physical exercise on the whole RT-distribution. Reaction time distribution analyses provide the opportunity to describe cognitive performance at a more fine-grained level and can provide much more information than more standard statistical summary measures like mean and variance. According to Sanders (1983), RT-distributions might serve as criteria to distinguish direct effects on computational stages from indirect effects on energetic mechanisms, but such speculation has been criticized (Smulders, Kenemans, Jonkman, & Kok, 1997). In this study, the analysis of the distributions was thus not used to make predictions regarding the energetic or computational nature of the exercise, but to better characterize the facilitating effect of exercise.

One of the best ways to obtain shape information from RT-distributions is to fit an explicit distribution function and use the parameters of this distribution as a summary of shape (Ratcliff, 1979). The Ex-Gaussian distributional model (Luce, 1986) can be used to provide quantitative measures of the distributional properties of a set of response times, and is a useful way to mathematically separate out the components of the shapes of RT-distributions into a set of summary parameters. According to this model, the distribution of reaction times can be characterized as a convolution of normal and exponential distribution functions. The Ex-Gaussian distribution has three parameters: mu (μ) and sigma (σ) describe the mean and the standard deviation of the normal component respectively, and tau (τ) describes the mean of the exponential component. Mu and sigma reflect the location of the leading edge of the distribution (i.e. the fastest response times), while tau reflects the size of the tail (i.e. the degree of positive skew). Delta plot analysis was also used to study the details of the RT-distributions. A delta plot represents the difference between the distribution curves of two experimental conditions, as a function of time, and reveals the dynamics of the effect of the manipulated factors. In the delta plot, a decrease was reflected in negative slopes for the higher response speed quantiles. In contrast, if we did not observe any change as reaction time increased, the size of the effect was the same for every response time whatever the response speed quantiles.

The aim of this experiment was to characterize the facilitating effect of exercise on the whole RT-distribution. To assess the evolution of cognitive performance during exercise, we also used performance evolution during blocks of 200 trials as an additional independent variable. Indeed, the time-course of effect sizes during the task might serve as criteria for the computational versus energetic nature of the effects of exercise (Sanders, 1983; Smulders *et al.*, 1997). According to these authors, if exercise is an energetic factor – that is, it alters the resource assigned to the reaction process – we should observe a larger effect size of exercise near the end of the task than at the beginning of the task. By contrast, if exercise is a computational factor – that is, it affects the complexity of the reaction process – we should not observe a difference between the effect sizes of exercise observed near the end of the task and at the beginning of the task.

Methods

Participants

The participants (4 females aged 22 ± 2 years and 7 males aged 25 ± 4 years; mean $\pm$ *s*) were experienced players in decisional sports (e.g. team sports, fighting sports and racket sports) who trained on a regular basis. Before taking part in the experiment, all participants signed informed consent forms and were made fully aware of the protocol. Maximal oxygen uptake ($\dot{V}O_{2max}$), maximal aerobic power, maximal heart rate and ventilatory threshold power (VTP) were individually determined in a preliminary protocol. Descriptive data for the participants are provided in Table I.

Apparatus

The participants were seated on a bicycle ergometer (Ergoline 800S) in front of a computer screen. The choice reaction time task consisted of hand-operating two levers as quickly and accurately as possible in response to visual stimuli. Four response signals were randomly presented in the centre of the display. Each signal corresponded to a specific response, namely a flexing or a stretching of the right or left wrist. Response time corresponded to the interval between the onset of the stimulus and the onset of a motor response. The inter-trial duration depended on the participant's swiftness to return to the starting position. A new trial began only after a 200 ms stabilization period in the starting position. Knowledge of results was given at the end of each trial. These knowledge of results concerned the speed of the response or the type of error: anticipation (RT $<$ 150 ms), omission (RT $>$ 2000 ms), decision error (side and/or direction error).

Design and procedure

In a preliminary protocol, the participants performed a standardized maximal exercise test on an electrically braked stationary cycle ergometer (Ergoline 800S). After a 5 min warm-up at 75 W and a 3 min rest period, the test began at 25 W, and the workload was increased by 25 W every minute (Wasserman, Whipp, Koyal, & Beaver, 1973). The test ended when the participant was no longer able to cycle, despite encouragement. The participant breathed through a face mask (Hans Rudolph). The flow of expired gases was measured using a pneumotachograph (Type 3 Hans Rudolph) and analysed breath-by-breath using an automated system (Medi Soft, Exp'air 1.26). Oxygen uptake, carbon dioxide production, expiratory flow and other classical respiratory parameters were monitored continuously and averaged every 15 s. A four-lead electrocardiogram recorded heart rate continuously. The last workload to be completed in this preliminary analysis was taken as maximal aerobic power.

After this test, and on return to the laboratory, the participants performed a familiarization session with the reaction time task. This session stopped when participants were able to carry out the task with a reaction time variability below 15% and an error rate below 5% (Sanders, 1980, 1990). This learning session minimized the possibility that practice effects would interfere with the effects of physical exercise and increased the output quality of stages during the choice reaction time task.

During the experimental session, which was performed on another day, participants performed two RT blocks of 200 trials. The total duration of a block was about 17 min. The first block was carried out at rest and the second block was performed during exercise (while cycling at 90% of VTP). This order was balanced across participants. A rest period was given to the participants between the two blocks. The duration of the period depended on the time necessary for participants' heart rates to return to resting values (between 5 and 10 min). When participants performed the task during exercise, the test started with a 3 min warm-up (without performing the reaction time task) and the pedal rate was freely chosen. Pedalling rate and heart rate were continuously recorded during the simultaneous task with Sport tester systems (Polar). No knowledge of results about these two variables was given to the participants. After the cardiorespiratory parameters and the pedal rate reached steady state (3 min after the beginning of the cycling task), the simultaneous task was begun.

Data analysis

The dependent variables for the following statistical analyses were heart rate, pedal rate, mean reaction time, reaction time variance, decision errors and the estimates of the three Ex-Gaussian parameters (μ, σ and τ) for the set of 200 trials obtained for each individual participant in each experimental condition. Graphical representation of the RT-distributions was performed using group reaction time distributions obtained using individual reaction time distributions "Vincentized" (Ratcliff, 1979) in 10 classes of equal size. The mean of each set was then averaged. The delta plot was estimated by plotting the difference between the values of the same set of two experimental conditions against the average of the same two values. The data presented are the mean values of each set averaged across participants. Only correct response times were used in the calculation of the measures. The data were analysed using an analysis of variance (ANOVA). For univariate repeated-measures ANOVA tests involving more than one degree of freedom, the

Table I. Characteristics of the participants (mean $\pm$ SD).

Age (years)	23.9 ± 3.9
$\dot{V}O_{2max}$ (ml $\cdot$ kg^{-1} $\cdot$ min^{-1})	45.2 ± 6.2
Maximal heart rate (beats $\cdot$ min^{-1})	186 ± 8.6
Maximal aerobic power, MAP (W)	297 ± 65
Ventilatory threshold power, VTP (W)	159 ± 28
90% VTP (W)	141 ± 27
50% MAP (W)	148 ± 31

Greenhouse-Geisser correction was conducted. In that case, the uncorrected degrees of freedom, the corrected *P*-value and the epsilon value were reported. *Post hoc* analyses using the Newman-Keuls test were conducted on all significant interaction s. Alpha was established at 0.05 for all analyses. Ex-Gaussian distribution fits were obtained using the PASTIS programme (Cousineau & Larochelle, 1997) for each participant and condition separately. An *a priori* choice of the distribution is given and the free parameters were deduced using the log likelihood technique (Cousineau & Larochelle, 1997).

Results

Here, we first report the physiological data, followed by the results related to reaction time. Regarding the design of the physiological data analyses, the data of one participant were lost because of data acquisition failure and hence the number of participants was reduced to 10.

Heart rate and pedal rate

For the blocks of 200 trials performed at rest and during exercise, heart rate was recorded during three intervals: 3 – 6 min, 8 – 11 min and 13 – 16 min after the beginning of the reaction time task. A 2 × 3 (exercise × period) ANOVA on heart rates revealed a significant interaction between exercise intensity and heart rate recording interval ($F_{2,18} = 8.42$, $P < 0.05$). Heart rate was significantly higher at 90% of VTP (136 beats · min^{-1}) than at rest (75 beats · min^{-1}). *Post hoc* analyses revealed an increase in heart rate during the exercise block but not during the resting block. Indeed, during exercise heart rate increased from 132 to 137 beats · min^{-1} between the 3 – 6 min and the 8 – 11 min intervals but remained relatively stable during the 13 – 16 min interval.

For the exercise block of 200 trials, pedal rate was recorded during the same intervals of time after the start of the reaction time task. Results revealed a significant effect of period on pedal rates ($F_{2,20} = 6.66$, $P < 0.05$). Pedal rate increased from 68 to 70 rev · min^{-1} between the 3 – 6 min and the 8 – 11 min intervals and reached 71 rev · min^{-1} during the 13 – 16 min interval.

Effects of physical exercise on mean reaction time, reaction time variance and proportion of errors

The effect of exercise on arsine transformed percentage of decision errors did not reach significance ($F_{1,10} = 4.2$, $P = 0.07$). The proportion of decision errors increased from 1.7% to 2.6% between rest and exercise. A detailed analysis presented below showed that this marginal effect, between rest and exercise conditions, did not reflect a trade-off between speed and accuracy. Also, it is possible that participants preserved the same strategy during both conditions.

The analysis of mean reaction time showed an improvement in performance during exercise ($F_{1,10} = 6.39$, $P < 0.05$). Mean reaction time was 13 ms shorter during exercise than at rest. No significant effect of exercise was observed on mean reaction time variance ($F_{1,10} = 0.15$, $P = 0.70$). The participants were faster without being more variable.

Mean reaction time and proportion of errors as a function of time on task

Reaction time evolution was assessed by dividing each block of 200 trials into eight sets of 25 trials. Statistical analyses were performed on mean reaction times of each of the eight sets. A 2 × 8 (exercise × set) ANOVA revealed a main effect of exercise ($F_{1,10} = 6.39$, $P < 0.05$) and set ($F_{7,70} = 4.00$, $P = 0.02$; $\varepsilon = 0.43$). The reaction time for the first set (S1 = 514 ms) was longer relative to the other seven sets (S2 = 488 ms; S3 = 492 ms; S4 = 488 ms; S5 = 486 ms; S6 = 484 ms; S7 = 485 ms; S8 = 490 ms). Although evolution of performance during exercise appeared visually to differ from rest (see Figure 1), no significant interaction was found between exercise and set ($F_{7,70} = 0.87$, $P = 0.53$). However, it is important to note that planned comparisons (comparison between rest and exercise for each pair of sets) revealed a larger facilitating effect at the end of the exercise. Indeed, a significant change in reaction time was observed on the sixth set of trials (− 18 ms; C6: $F_{1,10} = 6.66$, $P < 0.05$) and on the eighth set of trials (− 23 ms; C8: $F_{1,10} = 5.13$, $P < 0.05$).

For the arcsine transformation of the percentage of decision errors, a 2 × 8 (exercise × set) ANOVA revealed no significant main effect of exercise ($F_{1,10} = 4.2$, $P = 0.07$) or of set ($F_{7,70} = 0.66$, $P = 0.63$; $\varepsilon = 0.61$), and no interaction between these two factors ($F_{7,70} = 0.86$, $P = 0.54$).

Analyses of response time distributions

The Ex-Gaussian parameters were analysed using separate analyses of variance on each parameter. There was a main effect of exercise on mu (rest: 408 ms; exercise: 391 ms; $F_{1,10} = 9.27$, $P < 0.05$), but not on sigma (rest: 37 ms; exercise: 32 ms; $F_{1,10} = 1.31$, $P = 0.28$) or on tau (rest: 89 ms; exercise: 94 ms; $F_{1,10} = 0.26$, $P = 0.62$). We observed a shift of the distribution towards the left without modification of the form of the RT-distribution. Exercise induced a major generalized improvement of the whole RT-distribution. Delta plots showed that the benefit of exercise was small and consistent (10 – 15 ms) throughout the entire range of reaction times (Figure 2).

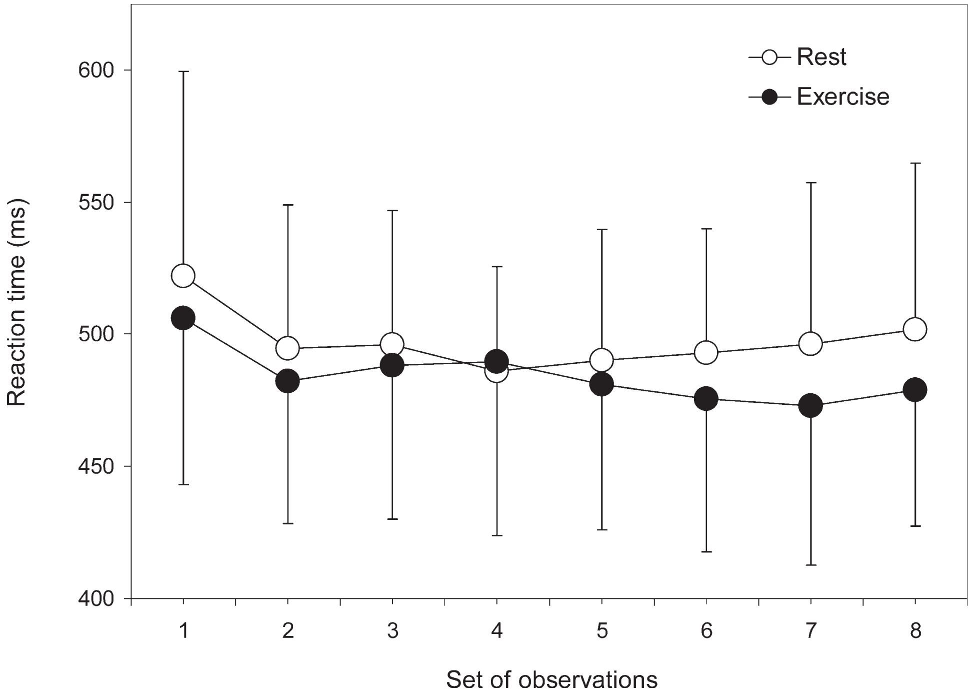

Figure 1. Mean reaction time and standard deviation (ms) as a function of time during the resting and exercise conditions. Reaction time was 13 ms shorter during exercise than at rest. Reaction time for the first set was lengthened relative to the other seven sets. Despite the fact that performance's evolution during exercise seems visually differ from rest, interaction between exercise and set was not significant.

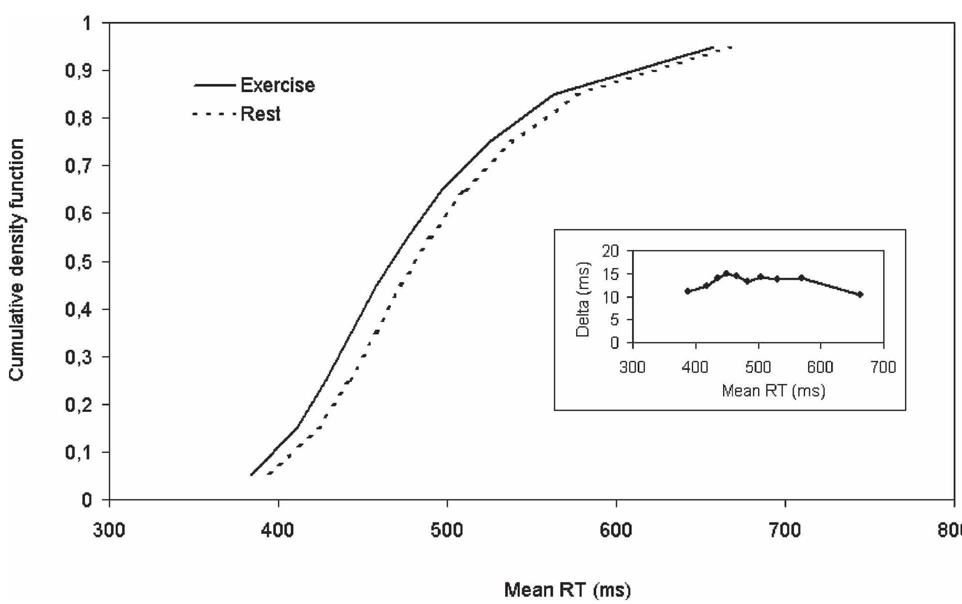

Figure 2. Reaction time distribution and delta mean plots (ms) between rest and exercise. The effect of exercise induced a shift of the distribution towards the left without modification of the form of the RT-distribution. Delta plots curves showed that the benefit effect was small but consistent throughout the whole of the deciles (10 – 15 ms).

Discussion

In line with the results of previous studies, our results revealed an improvement in cognitive performance during sub-maximal moderate exercise. Although Chmura *et al.* (1994, 1998) reported that optimal reaction time performance was elicited at exercise intensities after the participants had reached their catecholamine thresholds, improvements in cognitive performance can occur before ventilatory threshold power has been reached. In addition to a facilitating effect of exercise on mean reaction time, we observed a shift of the RT-distribution linked to a generalized facilitating effect of exercise on reaction time performance. In other words, the entire range of reaction times is affected by the same time constant. During exercise, heart rates attest that the physiological solicitation was in accordance with the aims of the study. Indeed, the stress induced by exercise generated an increase in heart rates, which was not observed during the resting block. As expected, we observed changes in physiological functions accompanied by a speeding up of cognitive performances during exercise. Participants became faster without being more variable or less accurate. As suggested by Peyrin, Pequignot, Lacour and Fourcade (1987), this mental improvement during exercise might be the consequence of central noradrenergic activation.

Regarding the time spent on task, results did not reveal differences between the effect size of exercise observed at the beginning of the task and the effect size observed at the end of the task. This observation is difficult to interpret. Indeed, ANOVA does not allow evaluation of the probability of type II error. Furthermore, the curves presented in Figure 2 suggest that the evolution of performance could differ between exercise and rest. Thus, further experiments are required to distinguish the computational versus energetic nature of the effects of physical exercise.

In conclusion, our aim was to study the facilitating effects of physical exercise on cognitive processes using a RT-distribution analysis. The results suggest that during exercise the participants were faster without being more variable or less accurate. In addition, the results of the distributional analyses lead us to conclude that the effect of exercise on reaction time performance was due to a major generalized improvement of the whole response time distribution. The beneficial effect was small but consistent throughout the entire range of reaction times (10–15 ms). This means that reaction time during exercise is a linear function of reaction time at rest.

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References

Arcelin, R., Brisswalter, J., & Delignières, D. (1997). Effect of physical exercise duration on decisional performance. *Journal of Human Movement Studies*, *32*, 123–140.

Arcelin, R., Delignières, D., & Brisswalter, J. (1998). Selective effects of physical exercise on choice reaction processes. *Perceptual and Motor Skills*, *87*, 175–185.

Brisswalter, J., Legros, P., & Delignières, D. (1994). Interactions entre processus cognitifs et physiologiques. *Science et Motricité*, *23*, 25–31.

Chmura, J., Krysztofiak, H., Ziemba, A. W., Nazar, K., & Kaciuba-Uscilko, H. (1998). Psychomotor performance during prolonged exercise above and below the blood lactate threshold. *European Journal of Applied Physiology and Occupational Physiology*, *77*, 77–80.

Chmura, J., Nazar, K., & Kaciuba-Uscilko, H. (1994). Choice reaction time during graded exercise in relation to blood lactate and plasma catecholamine threshold. *Journal of Sports Medicine*, *15*, 172–176.

Cousineau, D., & Larochelle, S. (1997). PASTIS: A program for curve and distribution analyses. *Behavior Research Methods, Instruments, and Computers*, *29*, 542–548.

Davranche, K., & Audiffren, M. (2002). Effects of a low dose of transdermal nicotine on information processing. *Nicotine and Tobacco Research*, *4*, 275–285.

Davranche, K., & Audiffren, M. (2004). Facilitating effects of exercise on information processing. *Journal of Sports Sciences*, *22*, 419–428.

Delignières, D., Brisswalter, J., & Legros, P. (1994). Influence of physical exercise on choice reaction time in sports experts: The mediating role of resource allocation. *Journal of Human Movement Studies*, *27*, 173–188.

Luce, R. D. (1986). *Response time: Their role in inferring elementary mental organization.* New York: Oxford University Press.

McMorris, T., & Graydon, J. (1996). The effect of exercise on the decision-making performance of experienced and inexperienced soccer players. *Research Quarterly for Exercise and Sport*, *67*, 109–114.

McMorris, T., & Graydon, J. (1997). The effect of exercise on cognitive performance in soccer-specific tests. *Journal of Sports Sciences*, *15*, 459–468.

McMorris, T., & Graydon, J. (2000). The effect of incremental exercise on cognitive performance. *International Journal of Sport Psychology*, *31*, 66–81.

Paas, F. G. C., & Adam, J. J. (1991). Human information processing during physical exercise. *Ergonomics*, *34*, 1385–1397.

Peyrin, L., Pequignot, J. M., Lacour, J. R., & Fourcade, J. (1987). Relations between catecholamines or 3-methoxy 4-hydroxy phenylglycol changes and the mental performance under submax exercise in men. *Psychopharmacology*, *93*, 188–192.

Ratcliff, R. (1979). Group reaction time distributions and analysis of distribution statistics. *Psychological Bulletin*, *86*, 446–461.

Sanders, A. F. (1980). Stage analysis of reaction process. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 331–354). Amsterdam: North-Holland.

Sanders, A. F. (1983). Towards a model of stress and human performance. *Acta Psychologica*, *53*, 61–97.

Sanders, A. F. (1990). Issues and trends in the debate on discrete vs. continuous processing of information. *Acta Psychologica*, *74*, 123–167.

Smulders, F. T., Kenemans, J. L., Jonkman, L. M., & Kok, A. (1997). The effects of sleep loss on task performance and the electroencephalogram in young and elderly subjects. *Biological Psychology*, *45*(1–3), 217–239.

Sternberg, S. (1969). The discovery of processing stages: extensions of Donders' method. *Acta Psychologica*, *30*, 276–315.

Sternberg, S. (1998). Discovering mental processing stages: The method of additive factors. In D. Scarborough & S. Sternberg (Eds.), *An invitation to cognitive science, Vol. 4: Methods, models, and conceptual issues* (pp. 703–863). Cambridge, MA: MIT Press.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychologica*, *112*, 297 – 324.

Wasserman, K., Whipp, B. J., Koyal, S. N., & Beaver, W. L. (1973). Anaerobic threshold and respiratory gas exchange during exercise. *Journal of Applied Physiology*, *35*, 236 – 243.

Yagi, Y., Coburn, K. L., Estes, K. M., & Arruda, J. E. (1999). Effects of aerobic exercise and gender on visual and auditory P300, reaction time, and accuracy. *European Journal of Applied Physiology and Occupational Physiology*, *80*, 402 – 408.