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SELECTIVE EFFECTS OF PHYSICAL EXERCISE ON CHOICE REACTION PROCESSES

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Summary.—The aim of the present study was to examine the effects of a moderate-intensity exercise (60 % of maximal aerobic power) on specific information processing mechanisms. Twenty-two students completed three 10-minutes exercise bouts on a bicycle ergometer. Concomitantly, participants performed six manual choice-reaction tasks manipulating task variables (Signal Intensity, Stimulus-Response Compatibility and Time Uncertainty) on two levels. Reaction tests, randomly ordered, were administered at rest and during exercise. A significant underadditive interaction between Time Uncertainty and exercise was found for the highest quartiles of the distribution of reaction times. No other interaction effects were obtained for the other variables. These results provide reasonable support that moderate aerobic exercise showed selective rather than general influences on information processing.

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The suggestion that physical exercise independently and differentially affects separate aspects of cognitive mechanisms has already substantial support in the literature (Fleury & Bard, 1987, 1990; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996; Hancock & McNaughton, 1986; Paas & Adam, 1991). However, divergent results were found on the information-processing locus of these effects. Among the possible contributors are the diverse computational requirements of the cognitive task manipulated, such as: sensory thresholds (Mc Glynn, Laughlin, & Rowe, 1979) perceptual discrimination (Fleury & Bard, 1987) decision making (Paas & Adam, 1991) coincidence-anticipation (Fleury & Bard, 1990; Isaacs & Pohlman, 1991; Wrisberg & Herbert, 1976).

Recently, the interactions between cognitive and physiological processes have been mainly studied with reaction time procedures. These studies demonstrated contradictory effect of exercise on cognitive performance, particularly when the reaction task took place during exercise bouts. Results have shown an impairment of simple reaction time (Brisswalter, Durand, Delignières, & Legros, 1995; Legros, Delignières, Durand, & Brisswalter, 1992) whereas an improvement of choice reaction time has been reported (Adam, Teeken, Ypelaar, & Verstappen, 1997; Arcelin, Brisswalter, & Delignières, 1997;

Delignières, Brisswalter, & Legros, 1994; Durand, Bourrier, & Legros, 1991; Paas & Adam, 1991).

Traditionally, the effect of physical exercise on cognitive performance was explained as shifts in the activation levels of the central nervous system (Gutin, 1973). The well known inverted U-shaped relationship (Yerkes & Dodson, 1908) between arousal and performance is proposed as the major contributing factor in previous studies (Levitt & Gutin, 1971; Salmela & Ndoye, 1986; Sjoberg, 1968). However, Gould and Krane (1992) point out three major methodological problems affecting studies on the relationship between arousal and performance. Controversies exist over (i) terminology of the concept of arousal and related states, (ii) the unidimensionality of this relationship, and (iii) measurement of performance in terms of outcomes rather than processes.

Several reviews on the associations between exercise and cognition (e.g., Tomporowski & Ellis, 1986) suggested that various stressors have different effects on specific cognitive processes. This specificity of relationships between biological energy states and information processing mechanisms (Hockey, Gaillard, & Coles, 1986) is the essential assumption of some explanatory models (Humphrey & Revelle, 1984; Sanders, 1983; Tucker & Williamson, 1984). With regard to the contradictory effect of exercise previously described, we hypothesized complex relationships between specific influences of exercise on computational mechanisms.

The Sanders' model assumes the existence of energetical mechanisms, computational processes and their relationships. Task variables and inferred computational processes were derived from the additive factor method (Sternberg, 1969) in the context of the choice reaction time. The optimal functioning of the computational processes is affected by at least three energetical generators (i) arousal system - related to the alerting effect of sensory inputs, (ii) activation sytem - which maintains the tonic readiness for motor action, and, (iii) effort mechanisms- related to decision-making and implicated in the coordination between arousal and activation. The innovative approach of the cognitive-energetic model concerns the selective effects of suboptimal conditions (state manipulations) on the choice reaction time performance. The methodology of additive factors has yielded consistent results in studying these cognitive-energetic relations (e.g., Frowein & Sanders, 1978; Sanders, Wijnen, & van Arkel, 1982).

Within this framework, an interaction between a state variable and a task variable implies an effect of that state variable on the energetic generator linked with the specific computational process (Sanders, 1983; Van der Molen, Somsen, Jennings, Nieuwboer, & Orlebeke, 1987). Furthermore, in order to distinguish between effect of a task variable and effect of a state variable on computational processes, Sanders (1983) argued that these variables presented different properties on the distribution of reaction times. Tasks variables usually have their effect on the whole reaction times distribution, whereas the effect of state variables is located at the higher end and should be absent at the lower end of the distribution. Consequently, on the one hand, three tasks variables were used in our experiment: Signal Intensity, Signal-Response Compatibility and Time Uncertainty which have been shown to yield a robust additive relationship (e.g., Sanders, 1980). Moderate-intensity exercise was the state variable. On the other hand, an analysis of the highest and the lowest quartile values of the distribution of reaction times was proposed.

The aim of the present study was to analyse and to compare combined influences of each task variable and physical exercise on computational processes. Because the direction and the magnitude of relationships between exercise and cognition were unclear, we made the hypothesis that exercise would have specific effects on the processing mechanisms, as opposed to a general one.

Method

Subjects

Twelve females and twelve males (M age = 23.5, SD= 4.3 yr.), volunteered to participate in this experiment. These subjects were physical education students and selected to have no specific expertise in decisional sports (Delignières, et al., 1994). To be homogeneous in physiological demand required by the exercise bouts, a preliminary graded exercise test of VO_2max determination was assessed for each subject. Mean VO_2max were respectively for women, 47.7 ml. min. $^{-1}$ kg.$^{-1}$ (SD=3.7) and for men, 59.9 ml. min. $^{-1}$ kg.$^{-1}$ (SD=10.5).

Materials

During all experimental tests, the subjects were seated on a bicycle ergometer (Miditronic). In order to control the physical characteristics of subjects, the experimental device could be adapted for each subject. The forearms were placed on elbow rests and the joysticks were adjusted to be tilted only with the thumb. Between the handlebars of the ergometer, the number of revolutions per minute and power output were displayed on a screen. Heart rate was recorded continuously in all sessions with a Sport tester PE 3000 system (Polar). The ambient light was fixed to 60 lux by using an exposure meter (Lunasix 3, Gossen).

The manual two-choice reaction task was performed by using a computer connected with two joysticks, fixed in front of the ergometer handlebars. Two empty squares (6 x 6 cm) were horizontally lined up on the center of the screen, adjusted to the subject's eye-level, drawn in yellow on blue. When one of the squares became filled with red, the subjects were asked to respond as quickly and accurately as possible by tilting the appropriate joystick.

A warning signal appeared 1200 msec. after the preceeding response. The signal-response compatibility corresponded with the natural relationship between the signal and the response and the duration of the foreperiod was fixed (1150 msec.). Latencies faster than 160 msec. were considered as anticipated responses and consequently, as errors. Reaction time and choice error were continuously monitored by the computer but no feedback concerning the cognitive performance was revealed to participants during the tests.

This apparatus allowed administration of three reaction-time tasks of increasing difficulty. In the Low Signal Intensity condition, the signal was degraded by changing both the size of the square (1x1 cm) and the contrast of the signal (yellow on light blue). In the Signal-Response Incompatibility condition, the compatibility was altered by changing the natural relationship between the signal and the response. The subjects responded to the left signal by tilting the right joystick and conversely, for the right signal the left joystick. In the Varied Time Uncertainty condition, the duration of foreperiod was changed to a long variable condition (from 5500 msec. to 8900 msec.). Sequence of tasks and levels of difficulty were varied randomly between subjects.

Procedure

Subject was tested in three sessions across 10 days. In the aim of maximal standardization of the procedure, the testing sessions were completed on separate days (Gutin, 1973) and at the same time of day (Becque, Katch, Marcks, & Dayeur, 1993).

The first session (Session 1) was an incremental maximal test of VO_2. Each participant had to pedal on the cycle ergometer at 60 rpm until volitional exhaustion (from Storer, Davis, & Caiozzo, 1990). The test started with a warm-up (6 minutes at 60 W) and then, the workload was increased by 30 W every minute until exhaution. VO_2max was attained with the following criteria : (i) a plateau in volume of O_2 uptake, (ii) heart rate near the maximal age-predicted heart rate and, (iii) a respiratory exchange ratio above 1.1 (Lacour & Flandrois, 1977). Expired gases (Oxycon) and heart rate were collected continuously. The Maximal Power reached with VO_2max was recorded. Before this test, a period of training with reaction-time tasks was proposed to the subjects. They were instructed to respond as quickly and accurately as possible: accuracy of response was fixed to keep choice errors below 5% for each task condition (Sanders, 1983).

During the second session (Session 2, baseline performance), each subject without pedalling on the cycle ergometer, was presented with the six conditions of reaction tasks (30 trials per condition), during 10 minutes duration per task. Heart rate was continuously monitored from 3rd to 10th minutes of the resting test.

During the third session (Session 3), the subject successively exercised three submaximal bouts, selected to represent 60% of Maximal Power for 10 minutes. Pedalling rate was freely chosen by the subject, and was continuously monitored. Between the successive exercise bouts, a resting period was allowed until individual heart rates corresponded to the at-rest level. After the heart rate had reached a steady-state (minute 3 of the exercise bout), the participant performed 30 trials per reaction task. During each submaximal bout only one task variable was manipulated at two levels of difficulty. The order of Sessions 2 and 3 was varied randomly between subjects.

Statistics

The reproducibility of physiological requirement between the three exercise tests was examined by using one-way analysis of variance with repeated measures using heart rate as the dependant variable. Error rate was analysed after arcsine transformation (Winer, 1971). A two (Session) by two (Difficulty) two-way analysis of variance for each task with repeated measurements on both factors was performed using error rate and mean reaction time as dependent variables. The analysis of quartile data was determined from the highest and lowest quartile values of the reaction times distribution for each subject and condition (e.g., Sanders, et al., 1982). A similar two-way analysis of variance with repeated measures was performed using first quartile and third quartile of mean reaction time. The Newman-Keuls test was used for post hoc comparisons of mean differences between conditions. Probabilities of .05 or less were considered as significant.

Results

For the resting value of heart rate, no significant differences were found between tests during Sessions 1, 2, and 3. During Session 3, when heart rate was expressed in percent of maximal heart rate (Karnoven & Vuorimaa, 1988) data showed for all task variables that the physiological requirement of exercise was strictly aerobic: 61.8, 60.5, and 61.2 % of maximal heart rate ($p > .05$).

Mean reaction time, error rate and third quartile of reaction times distribution are reported in Table 1. For Signal Intensity, Stimulus-Response Compatibility and Time Uncertainty variables, the analysis of variance indicated that both the effects of Difficulty ($p<.0001$) and Session ($p<.0001$) on mean reaction time, first quartile and third quartile values were statistically significant.

Analysis showed a main effect of Session on error rate for Signal Intensity ($F_{1,23}=12.74$; $p<.001$) but no significant changes for Stimulus-Response Compatibility and Time Uncertainty (respectively, $F_{1,23}=.20$ and $F_{1,23}=.04$; $p>.05$). No significant interaction of Session by Difficulty was found for Signal Intensity, Stimulus-Response Compatibility and Time Uncertainty on error rate.

For Signal Intensity, Stimulus-Response Compatibility and Time Uncertainty, an additivity pattern result was found on mean reaction time and first quartile between Session and Difficulty ($p>.05$). This additive pattern was confirmed for Signal Intensity and Stimulus-Response Compatibility on third quartile. Conversely for Time Uncertainty, analysis indicated an underadditive interaction ($F_{1,23}=4.87$, $p<.05$) between Session and Difficulty on third quartile. Post hoc analysis demonstrated a significant improvement of reaction time performance during exercise, respectively for Fixed Time Uncertainty. ($F_{1,23}=6.01$; $p<.025$) and for Varied Time Uncertainty ($F_{1,23}=21.61$, $p<.0001$).

TABLE 1

Absolute mean reaction time (msec), third quartile of reaction times distribution (msec) and error rate (%) as function of exercise and difficulty of processing

Task Conditions		Signal Intensity High	Signal Intensity Low	Compatibility Compat.	Compatibility Incompat.	Time Uncertainty Fixed	Time Uncertainty Varied
Mean reaction time							
Baseline	M	254.32	305.98	258.07	309.24	254.43	280.03
	SD	18.94	19.91	16.67	21.12	17.10	21.66
Exercise	M	240.12	291.51	241.88	289.73	242.50	261.92
	SD	18.87	17.36	15.76	27.10	25.75	24.21
Third Quartile of reaction time							
Baseline	M	275.40	325.50	277.68	337.57	272.10	297.75
	SD	24.46	20.68	18.68	27.15	17.96	28.06
Exercise	M	258.64	310.58	261.44	317.92	262.65	276.54
	SD	22.50	18.82	15.62	29.15	26.34	26.80
Error rate							
Baseline	M	3.54	4.31	1.04	2.78	2.71	3.19
	SD	4.54	2.86	2.07	3.05	3.60	4.22
Exercise	M	1.25	2.92	1.67	3.19	2.50	2.78
	SD	2.21	3.44	3.87	3.74	3.29	2.34

Discussion

The present results provide support for the hypothesis that information processing speed was affected differentially by moderate exercise. This finding evoke a specific relationship between energetic mechanisms and computational processes required in the task (Humphrey & Revelle, 1984; Landers, 1980; Oxendine; 1984; Sanders, 1983). Therefore, the unidimensional hypothesis of exercise-induced activation, previously used as the major interpretation (e.g., McMorris & Keen, 1994), seems to be revisited when studying the interactions between exercise and cognitive processes. However, several methodological limitations have to be considered.

Firstly, the reproducibility of the physiological requirements of sub-maximal tests should be altered with the influence of fatigue induced by successive exercise bouts (Brisswalter, Legros, & Delignières, 1994). However, the analysis of steady-state heart rate during each exercise test (Session 3) has shown a great stability. Consequently, our results confirm the reproducibility of physiological requirements observed in a similar protocol by Becque, et al. (1993).

Secondarily, the additive factors methodology suggests that exercise should not affect the structure but only the duration of computational mechanisms (Sanders, 1983). In our study, the improvement of reaction time performance with acute exercise, particularly on response speed was consistent with previous studies (Delignières & Brisswalter, 1995; Pass & Adam, 1991; McMorris & Graydon, 1996). However, the stability of response accuracy during exercise was shown only for Stimulus-Response Compatibility and Time Uncertainty variables. For Signal Intensity, in contrast, moderate exercise significantly decreased the error rate. We assumed that this finding was not related to a trade-off phenomenon (Pachella, 1974) but to a possible effect of effort mechanism in compensating the transient malfunctioning of arousal induced by sensory inputs. According to Sanders (1980) the Signal Intensity variable affects an earlier processing stage labeled 'stimulus preprocessing'. In line with the hypothetic 'immediate arousal' mechanism (Sanders, 1983) the Signal Intensity manipulations altered the temporary state of the arousal system. Consequently, during at-rest condition this arousing effect produces rapid but badly reactions (respectively for error rate, in High and Low Signal Intensity conditions: 3.54% and 4.31%). Conversely, we suggested that during exercise the subject is optimally prepared and the effect of 'immediate arousal' should be suppressed by a possible compensatory activity of effort mechanism. The additivity pattern between Signal Intensity and exercise could be explained by the case of full compensation of effort mechanism wich produces a nil result on reaction times. However, if this specific allocation of effort with exercise could not be easily tested in such experiment, it must be considered in future experiments (e.g., Delignières, et al., 1994).

The major finding of our research is that moderate exercise differently affects separate aspects of information-processing mechanisms as opposed to a general effect on cognitive functioning.

On the one hand, the underadditive interaction between Session and Difficulty for Time Uncertainty variable is mainly located at the highest end of the reaction times distribution. Conversely, this finding was not obtained on the first quartile and on absolute mean from the reaction times. Therefore, in accordance with Sanders's assumptions (1983, p.83) our results demonstrated that exercise is really a state variable which behaves like a stressor providing 'indirect energetic effects' on computational mechanisms.

On the other hand, comparing with the additivity patterns obtained for Signal Intensity and Stimulus-Response Compatibility, the underadditive interaction for Time Uncertainty provides clear support that exercise affects at least the motor side of the reaction process. With regards to Sanders' (1983) model, this specific relationship could be interpreted with the mediating role of nervous system activation at a specific stage labeled 'motor adjustment'. We could therefore hypothesize that exercise-induced activation increased during the foreperiod, in particular prior to the arrival of the stimulus. This effect could be explained by a dimunition of the distance to the 'motor action limit' during the motor preparation (van der Molen, et al., 1987). Furthermore, our results demonstrated that this specific improvement of reaction time is more effective when Time Uncertainty increases, thus when the subject was kept uncertain about the arrival of the signal response. If this hypothesis is valid, the measurement of heart rate deceleration (van der Molen, et al., 1987) or cortical potentials (Lardon & Polish, 1996) during the preparatory phases of the reaction process may provide interesting information about the selective effect of exercise on computational processes.

In summary, the results of the present study suggest that the effects of moderate exercise on cognitive functioning are mediated predominantly by specific influences of activation in the later stages of information processing. Secondarily, a mediating role of the effort mechanism in compensating the arousal system could be evoked. However, future replication is necessary to validate these results.

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