Exploring the relationship between exercise-induced arousal and cognition using fractionated response time

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Chang, Y.K., Etnier, J.L., & Barella, L.A. (2009). Exploring the relationship between exercise-induced arousal and cognition using fractionated response time. *Research Quarterly for Exercise and Sport, 80(1)*, 78-86.

Abstract:

Although a generally positive effect of acute exercise on cognitive performance has been demonstrated, the specific nature of the relationship between exercise-induced arousal and cognitive performance remains unclear. This study was designed to identify the relationship between exercise-induced arousal and cognitive performance for the central and peripheral components of a response time task at two different levels of task difficulty. Sixteen male participants performed both simple and choice response time tasks at eight different arousal levels (from 20% to 90% heart rate reserve). Performance on the simple and choice response time tasks was examined after fractionating the response time into its central component, premotor time, and peripheral components, motor, and movement time. A priori trend analysis was used to test both linear and quadratic relationships. Results indicated that exercise-induced arousal has a positive influence on the peripheral components of response time tasks; however, it has a limited impact on the central components of these tasks.

Keywords: inverted-U hypothesis | fractionated response time

Article:

Historically, the relationship between a single exercise bout and cognitive performance has been recognized as an important research topic in sport and exercise psychology. Although the results of empirical studies have not been consistent, when summarized using either narrative or meta-analytic techniques a positive overall relationship between acute exercise and cognitive performance has been reported (Brisswalter, Collardeau, & Arcelin, 2002; Etnier et al., 1997; McMorris & Graydon, 2000; Tomporowski, 2003). Given this generally positive relationship, the next important step for furthering our understanding of that relationship is to investigate underlying mechanisms and the specific nature of the dose-response relationship.

Physiological arousal as a potential mechanism has received attention in the empirical literature (e.g., Adam, Teeken, Ypelaar, & Verstappen, 1997; Chmura, Nazar, & Kaciuba-Uscilko, 1994; Davranche & Audiffren, 2004; McMorris & Graydon, 2000; Paas & Adam, 1991; Tomporowski, 2003). Although a number of studies have been conducted to test the relationship between exercise-induced arousal and cognitive performance, the findings of these studies have been equivocal (for review, see McMorris & Graydon, 2000). For example, some studies have been interpreted as supporting a linear facilitative relationship (Aks, 1998; Allard, Brawley, Deakin, & Elliot, 1989; McMorris & Graydon, 1996), as supporting an inverted-U relationship (Brisswalter, Durand, Delignieres, & Legros, 1995; Chmura et al., 1994; Levitt & Gutin, 1971; Martens & Landers, 1970; Reilly & Smith, 1986; Salmela & Ndoye, 1986; Sonstroem & Bernardo, 1982), or as reporting no relationship between arousal and cognitive performance (Côté, Salmela, & Papathanasopoulu, 1992; Sjoberg, 1980; Sjoberg, Ohlsson, & Dornic, 1975).

In many of these studies, response time tasks were used as the measure of cognitive performance, and in recent studies researchers fractionated response time to delineate the relationship between exercise-induced arousal and the central and peripheral components of the task. This is important, because both unidimensional (e.g., the inverted-U hypothesis) and multidimensional (e.g., allocatable resource theories) theories predict differential relationships between exercise-induced arousal and cognition based on factors such as task type, task complexity, and demands on central nervous system resources (McMorris & Graydon, 2000). Arent and Landers (2003) assessed response time and its components (reaction time and movement time) following performance of one of eight levels of exercise-induced arousal. Their results demonstrated that arousal affects both reaction time and response time in a quadratic trend, as hypothesized based on the inverted-U hypothesis; however, their results also showed that the relationship between arousal and movement time was linear. Arent and Landers concluded that the inverted-U hypothesis is appropriate for explaining the arousal-performance relationship for the task components that require more cognitive ability or central processes, while a linear relationship explains the relationship for task components requiring more motor or peripheral processes.

Davranche, Burle, Audiffren, and Hasbroucq (2005) advanced this line of inquiry by further fractionating reaction time into premotor and motor components to identify the effects of exercise-induced arousal on the central and peripheral components of reaction time. Their results indicated that while exercising at 50% maximal aerobic power resulted in better reaction time compared to a resting condition, the effects were evident only for motor time but not premotor time. Similarly, Kamijo et al. (2004) tested the relationship between exercise-induced arousal and premotor time and reported the relationship was not statistically significant. A limitation of the Davranche et al. (2005) and the Kamijo et al. (2004) studies is that the relationship between exercise-induced arousal and reaction time components were only tested at one exercise intensity as compared to rest (Davranche et al., 2005) or three exercise intensities (Kamijo et al., 2004); therefore, the relationship has not been clearly defined. Thus, the primary purpose of this study was to use exercise to induce multiple ($N = 8$) levels of arousal to identify the linear or curvilinear relationships between exercise-induced arousal and the peripheral and central components of a reaction time task.

With regard to task type, most studies examining the arousal-performance relationship with response time tasks have not examined the potential for task difficulty to influence the relationship between exercise-induced arousal and performance (e.g., Arent & Landers, 2003; Brisswalter, Arcelin, Audiffren, & Delignieres, 1997). Given the suggestion that this relationship might differ as a function of task difficulty (Humphreys & Revelle, 1984; McMorris & Graydon, 2000; Spence & Spence, 1966) a secondary purpose of this study was to add to the extant literature by examining the relationship between exercise-induced arousal and central and peripheral components of a response time task at two different levels of task difficulty.

Method

Participants

Sixteen male participants ranging in age from 20 to 35 years (*M* = 27.92 years, *SD* = 2.83) with no physical disabilities were recruited from flyers and advertisements posted on the university's bulletin boards. All were right-hand dominant based on self-report and had normal vision or corrected to normal vision. Risks to participants were minimized by a review of the Physical Activity Readiness Questionnaire (PAR-Q) and a medications history prior to participation.

Measures

Bicycle Ergometer Test. A ramped exercise protocol performed on a bicycle ergometer (Excalibur Sport; Seattle, WA) was used to evaluate maximal heart rate (HR). Each participant adjusted the saddle height vertically and the handle distance horizontally for comfort before beginning. The exercise protocol consisted of a 5-min warm-up, progressive cycling, and a cool-down period. In the warm-up stage, participants pedaled at a low resistance level for 5 min to warm up and provide an opportunity to adjust the bicycle seat and handlebars as needed. In the progressive cycling stage, participants were instructed to pedal at a cadence of 70 rpm, and workload was increased by 25 W every minute until the participant reached voluntary exhaustion (American College of Sports Medicine, 2006). Maximal heart rate was identified as the highest heart rate attained. Participants pedaled from 8 to 11 min (*M* = 8.75, *SD* = 0.77) before reaching voluntary exhaustion. The average maximal HR attained was 184.94 bpm (*SD* = 12.28), and the average resting HR was 68.75 bpm (*SD* = 9.90). After completing the progressive cycling stage, participants pedaled at a light intensity for the cool-down stage until their HR returned to within 15% of baseline, at which point the test was terminated.

Heart Rate Reserve. HR reserve is an accepted method for establishing various levels of exercise intensity (American College of Sports Medicine, 2006), and it is calculated as maximum HR minus resting HR (Karvonen, Kenthla, & Mustala, 1957). In this study, the target HR was calculated by multiplying HR reserve by the target intensity (as a percentage) and adding back the resting HR (e.g., if maximum HR = 200, resting HR = 50, and target intensity = 70%, the target HR would be (200 - 50)*70% + 50 = 155). In the present study, HR was monitored by a short-range radio telemetry device (Sport Tester Mode PE 3000; Polar Electro, Kempele, Finland). The monitor consists of an elastic band strapped around the chest to hold a rubber pad with a sensor and transmitter just below the sternum, and a wristband receiver/monitor that displays and records HR.

Response Time Equipment. Behavioral and physiological data were collected simultaneously with Lab View software, such that markers denoting the stimulus presentation, movement initiation, and movement completion were recorded and synchronized with the electromyographic (EMG) data. The handlebars and saddle on the ergometer were adjusted based on their recorded positions from the initial test. Participants sat on the ergometer directly facing a computer monitor, which presented stimuli as a circle in one of three locations (right, center, and left). Participants rested their right arm on the response board with their elbow flexed at 90° and shoulder abducted to 90° so that the arm was parallel to the ground. The response board was a fan-shaped wooden half-circle (40-cm radius and 180°) to the right of the ergometer and adjusted relative to the saddle height and individual's physique. In the response board were three (3 x 5 cm) holes, one each arced to the right, the center, and the left. Under each hole was a laser light and sensor, which was used to identify the precise time the participant's hand passed over the hole.

During the trials, participants were instructed to begin with their wrist over the center hole in the response platform. Based on the stimulus location displayed on the computer, participants were instructed to move their hand to the right or left (congruent with the direction of the stimulus) as quickly as possible so that their wrist crossed the appropriate target. After each trial, the participant returned to the center target, and a subsequent stimulus was presented after a variable period of 500–1,000 ms. During the simple response time tasks, participants were informed whether they would be moving to the right or left and they performed 10 trials. During the choice response trials, participants moved to either the right or left hole depending on the stimulus location. The choice cognitive task consisted of 20 trials (10 right and 10 left) presented randomly in each intensity condition. This number of trials was based on our pilot work, which indicated the most trials that could be reasonably completed at the higher arousal levels.

Procedure

Participants were asked to come to the laboratory on two separate days. On the first, they were asked to read and sign the consent form, which had been approved by the University's Institutional Review Board. They then completed the PAR-Q to determine eligibility for the study. Participants were then asked to sit quietly in a comfortable chair in a dimly lit room for 20 min to assess baseline HR. Maximum HR was then identified using the bicycle ergometer test.

On the second day, onsite pre-amplified fixed distance bipolar electrodes were affixed to the participant's right arm, and a ground/reference electrode was affixed to the left leg. Participants were first asked to tense the biceps and then the triceps in order to locate the center of the muscles. The triceps and biceps were expected to be the principal muscles involved in the response, because the participant's arm was supported by the response board so that the movement required only forearm flexion or extension (Brown, 2007; Etnier, Sibley, Pomeroy, & Kao, 2003). Participants' skin was rubbed with alcohol and lightly abraded with sandpaper to prepare for the electrode attachments. One bipolar electrode was affixed to record biceps activity, one was affixed to record triceps activity, and the ground electrode was affixed to the left leg.

All participants were asked to complete five practice/training trials in each condition prior to performing any exercise. These sessions were administered for both simple and choice response time tasks to ensure that participants understood the test directions. Participants used their right hand for both tasks and were asked to respond as quickly as possible. They had a 5-min warm-up period on the bicycle during which they pedaled at a low resistance level (20 W). Then they performed simple and choice response time tasks while cycling at eight different intensities ranging from very light to hard exercise: 20, 30, 40, 50, 60, 70, 80, or 90%, respectively. To minimize any "order effects," the presentation order of the arousal levels was randomized using a Latin-Squares design, with the only restrictions that the higher intensities (70%, 80%, and 90%) were never performed back-to-back and were not performed during the first trial block. These restrictions were to help minimize fatigue effects, minimize carry-over effects from the higher intensity conditions, and ensure that participants did not suffer a muscular injury from completing a high-intensity level at their first trial. Participants were asked to maintain a pedaling rate of 70 rpm, and the experimenter manipulated intensity by adjusting the watts on the bicycle ergometer. However, as determined during pilot testing, it was difficult for participants to maintain 20–40% HR reserve while pedaling. Therefore, they were instructed to sit on the bicycle quietly (20%) or pedal slightly (30% or 40%) with little or no resistance to achieve the target HR at these low intensities. Once participants reached the target HR, they were asked to maintain their HR for 1 min and then perform 10 simple response time trials in each direction and 20 choice response trials during pedaling. The presentation order of these trial blocks was randomized. Between each intensity level, participants were asked to rest on the bicycle until their HR returned to within 15% of resting HR (range = 5–25 min). Following these same procedures, participants performed eight intensity levels, with an average total testing time of 75 min.

Data Reduction and Statistical Analysis

Response time is defined as "the time from the presentation of an unanticipated stimulus to the completion of the response to the stimulus, and is the sum of reaction time and movement time" (Schmidt & Lee, 1999, p. 28). Reaction time is defined as "the time from the arrival of a suddenly presented and unanticipated stimulus, to the beginning of the response to that stimulus" (Schmidt & Lee, 1999, p. 27). Movement time is the time from beginning the response to movement completion and is essentially devoid of central processing. In this study, the beginning response was identified as breaking the light beam at the start location, and movement completion was identified by breaking the light beam at the end location. Reaction time can be further fractionated into premotor and motor time. Premotor time, primarily a function of central processing or cognition (Weiss, 1965), is the time from stimulus presentation to movement initiation, as identified from EMG activity. Motor time is the time from movement initiation, as identified from EMG activity, to the behavioral indication of the response initiation (identified by breaking the light beam at the start location), and it represents processes associated with the musculature (Weiss, 1965).

EMG activity data were analyzed using DATAPAC 2000. After rectifying the EMG, data were put through a forward and backward low pass filter at 5000 Hz using a Butterworth filter. In addition, the EMG data were processed using a centered (symmetrical) root mean square algorithm with a 100-ms time constant for each participant. Finally, peak amplitude was identified trial-by-trial as the first waveform that occurred within 1,000 ms of the stimulus presentation and had an amplitude greater than 3 standard deviations above the mean amplitude during the1,000-ms window. The time at which the peak amplitude occurred identified the movement initiation and, hence, marked the end of premotor time and the beginning of motor time.

Two data reduction steps were used to identify outliers for these outcome variables. First, erroneous data were identified separately for simple and choice response time tasks and were defined as values below 50 or above 500 ms on premotor or motor time. Second, outliers were eliminated for all premotor, motor, and movement time variables in both simple and choice response time tasks when values were greater than 2 standard deviations above or below the mean for each participant within each trial block. This resulted in 11.6% of trials being identified as outliers in the simple response time condition and 9.9% in the choice response time condition. Analyses were conducted with all trials included and the outliers omitted; and the results were similar using either approach. All results presented herein are with the outliers removed.

Premotor, motor, and movement times for simple and choice response time tasks were analyzed separately using repeated measure analyses of variance (ANOVA) with repeated measures on intensity (20, 30, 40, 50, 60, 70, 80, or 90% HR reserve). To test linear and quadratic relationships between exercise-induced arousal and cognitive performance, a priori trend analysis was used. Polynomial contrasts were used to follow up significant univariate effects. Order effects were also tested to identify any effects of the presentation order of intensity levels on the dependent variables. The significance level was set at $\alpha = .05$. Partial eta-squared (partial η2) is provided as a measure of effect size for significant effects. The Huynh-Feldt epsilon was examined to check the sphericity assumption, and multivariate tests of significance were used when the assumption was not met.

Results

Order effects were not significant for any dependent variables for either simple or choice response time tasks, $F(14, 168) = 0.94$–1.73, $p > .05$.

Premotor Time

Repeated measures ANOVA revealed no significant main effect for arousal on premotor time during the simple response time task, $F(7, 91) = 0.92$, $p > .05$, or the choice response time task, $F(7, 98) = 1.29$, $p > .05$.

Motor Time

There was a significant main effect for arousal on motor time for the simple response time task, $F(7, 91) = 2.40$, $p < .05$, partial η2 = 0.16. The trend analysis indicated a significant linear relationship between exercise-induced arousal and motor time, $F(1, 116) = 5.03$, $p < .05$ (see Figure 1a), such that motor time decreased as arousal increased. The quadratic trend was not significant, $F(1, 116) = 0.05$, $p > .05$.

There was also a significant main effect for arousal on motor time for the choice response time task, *F*(7, 98) = 3.12, $p < .005$, partial η2 = 0.18. The trend analysis indicated a significant linear relationship between exercise-induced arousal and motor time, *F*(1, 119) = 8.34, $p < .005$ (see Figure 1b), such that motor time decreased as arousal increased. The quadratic trend was not significant, *F*(1, 119) = 1.75, $p > .05$.

Figure 1a)

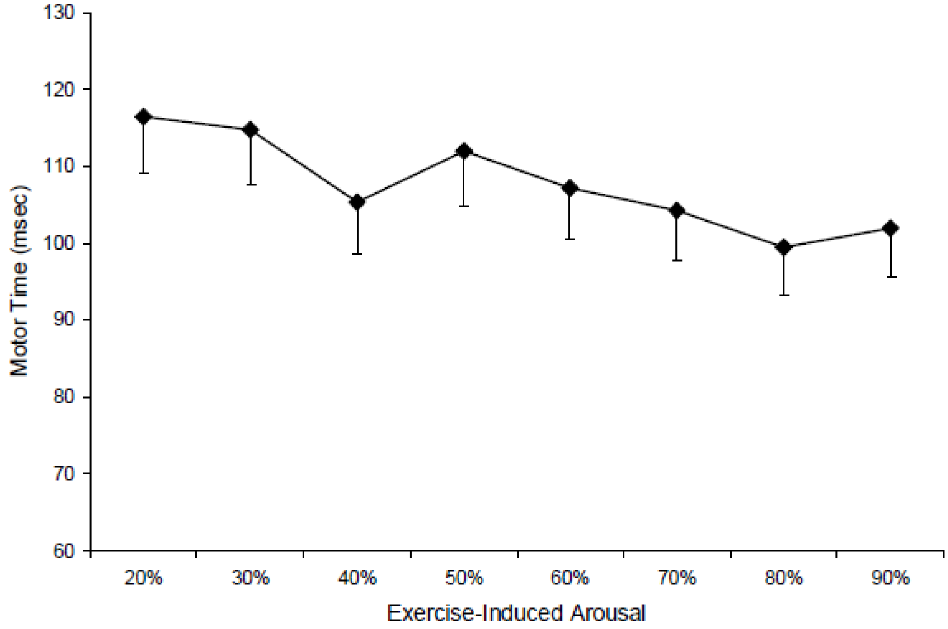

Figure 1b)

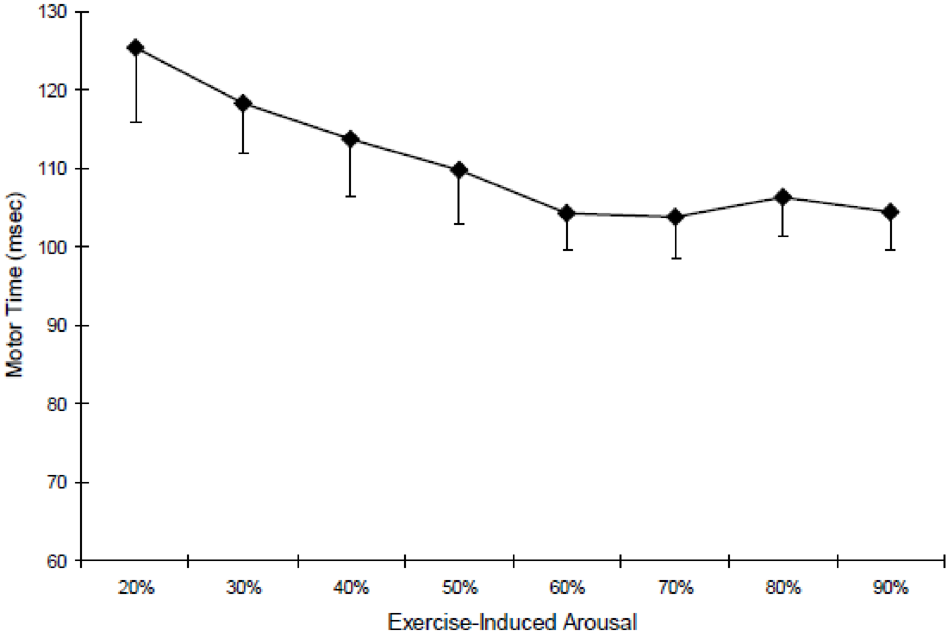

Figure 1. Motor time as a function of exercise-induced arousal (a = simple response time task, b = choice response time task.

Figure 2a)

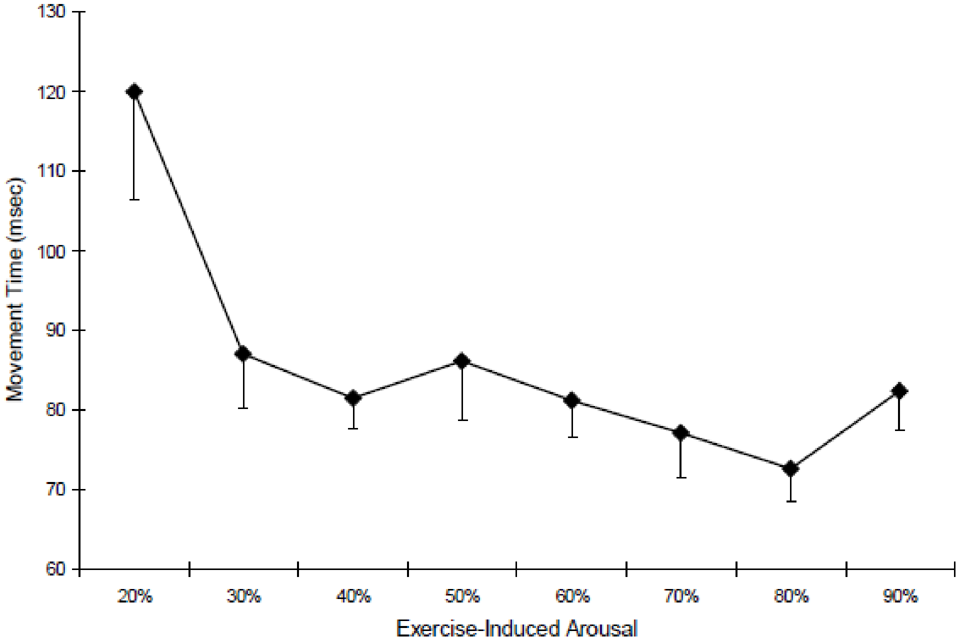

Figure 2b)

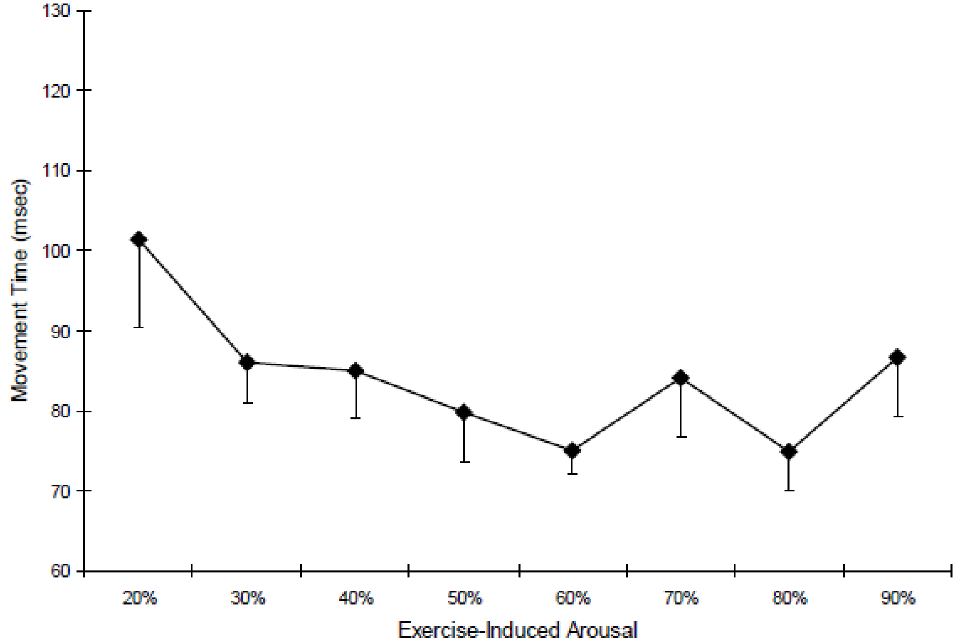

Figure 2. Movement time as a function of exercise-induced arousals (a = simple response time task, b = choice response time task.

Movement Time

There was a significant main effect for arousal, $F(7,105) = 5.95$, $p < .005$, partial η2 = 0.28. The trend analysis indicated a significant linear trend, $F(1, 120) = 15.07$, $p < .001$, and a significant quadratic trend, $F(1, 125) = 8.42$, $p < .005$, between arousal levels and movement time (see Figure 2a). Thus, movement time generally decreased with increasing arousal levels, but the quadratic trend suggests this effect is asymptotic with the relative increase in performance lessening as arousal increased at the higher intensities.

For the choice response time task, there was a significant main effect for arousal on movement time, $F(7, 98) = 2.20$, $p < .05$, partial η2 = 014, with the trend analysis indicating the relationship is quadratic, $F(1, 119) = 4.99$, $p < .05$ (see Figure 2b), but not linear, $F(1, 119) = 3.63$, $p > .05$. Thus, movement time became faster with increasing arousal level up to approximately 60% HR reserve at which point movement time remained relatively stable.

Discussion

Past research on the effects of different exercise intensities on response time was conducted on relatively few intensity levels and did not statistically test for linear or quadratic trends (Aks, 1998; Allard, et al., 1989; Arcelin, Delignieres, & Brisswalter, 1998; Davranche et al., 2005; Kamijo et al., 2004) or use fractionated reaction time to distinguish peripheral and central effects (Chmura et al., 1994; Côté et al., 1992; Levitt & Gutin, 1971). Thus, the present study adds to the knowledge base by using an a priori trend analysis to test both linear and quadratic relationships between exercise-induced arousal and the peripheral and central components of a response time task. In general, the results of this study indicate the effects of exercise-induced arousal are different for components of the response time task and, thus, emphasize the importance of decomposing response time into its constituents to further our understanding of the relationship between exercise-induced arousal and performance.

Results indicated no significant relationship between exercise-induced arousal and premotor time. These results are similar to past research that demonstrated exercise-induced arousal did not significantly affect premotor time when comparing rest to 50% maximal aerobic power (Davranche et al., 2005) or three exercise intensity levels (Kamijo et al., 2004). Thus, these findings suggest the effects of acute exercise previously demonstrated for response time tasks (Brisswalter et al., 1995: Levitt & Gutin, 1971; Paas and Adam, 1991; Reilly & Smith, 1986) were not due to effects on the central (or cognitive) task components. These results are consistent with conclusions drawn by McMorris and Graydon (2000) that on relatively simple cognitive tasks, such as the response time task used herein, there are sufficient resources such that increases in arousal do not provide any added benefit to performance.

In contrast to premotor time, there was a significant relationship between exercise-induced arousal and both motor and movement times. The data for motor time showed a significant linear relationship with exercise-induced arousal such that motor time decreased with increasing arousal levels. These findings are consistent with those of Davranche et al. (2005), who reported motor time was faster at 50% maximal aerobic power than at rest. Given that motor time largely reflects musculature functioning, this suggests that exercise-induced arousal has an impact on musculature functioning speed.

For movement time, our findings are consistent with those of Arent and Landers (2003) in demonstrating a positive linear relationship between exercise-induced arousal and movement time for a simple response time task. However, the results from this study differ from Arent and Landers in that significant quadratic relationships were observed for movement time at both levels of task difficulty. This finding is compatible with McMorris and Keen's (1994) prediction that performance speed should increase from rest to maximal exercise but should not differ between heavy and maximal exercise levels.

The explanation for why exercise-induced arousal had an impact on the peripheral task components but did not affect the central task components might rely on the mechanisms underlying the relationship. McMorris and Graydon (2000) and Chmura et al. (1994) suggested that increases in epinephrine and norpepinephrine are responsible for the relationship between exercise-induced arousal and performance. However, McMorris and Graydon pointed out that the changes in peripheral levels of epinephrine and norpepinephrine do not necessarily indicate changes in their levels in the central nervous system. Thus, these differing results may be due to the fact that increases in peripheral concentrations of epinephrine and norpepinephrine are more likely to have an impact on the peripheral components than the central components of the task (Genuth, 1998; Podolin, Munger, & Mazzeo, 1991). However, because both motor time and movement time are peripheral processes thought to be essentially devoid of cognitive contributions, the reason for the slightly different findings for those times in this study are not clear.

There are limitations of this study. Although many of our a priori hypotheses reached statistical significance and the results were consistent with past research, the relatively small sample size opens the possibility of a Type II error, and order effects (suggesting carryover effects due to the within-participants design) may have occurred but were not statistically significant because of a lack of statistical power. Additionally, because of the relatively small sample size, our study was under-powered to test the potentially moderating effect of task difficulty on the relationship between arousal and the response task components. Thus, our findings for the simple and choice response tasks are based only on individual interpretation not on a statistical comparison of the results.

Collectively, the results of this study suggest that exercise-induced arousal influences the peripheral components of response time tasks and has no impact on the central or cognitive components. However, given the meta-analytic evidence and conclusions from narrative reviews suggesting that acute exercise has a positive effect on cognitive performance, future research in this area is certainly warranted. One avenue for future research would be to use electroencephalographic techniques and event-related potentials to examine neuroelectric processes underlying cognition. Previous studies have shown that acute exercise might benefit neuroelectric processes underlying cognition that cannot be observed using behavioral measures (Kamijo et al., 2004; Magnie et al., 2000); however, these studies used three or fewer exercise intensity levels and, hence, did not provide a comprehensive test of dose-response relationships between exercise-induced arousal and these processes. Second, in this study the cognitive task type was not manipulated; given the minimal differences in the findings for the simple and choice response time tasks, the manipulation of task difficulty was clearly not very strong. Although studies have been conducted to test the effects of various intensities of acute exercise on more complex cognitive tasks such as those requiring attention and memory (Allard et al., 1989; Sjoberg, 1980), theory-driven research is needed to identify the task-specificity of the effects and explore the potential for task complexity to moderate the relationship between exercise-induced arousal and cognitive performance. Last, future research in this area will benefit from including multiple levels of exercise intensity and considering other indicants of arousal (e.g., epinephrine and norpepinephrine) to further our understanding of dose-response relationships and the mechanisms underlying these relationships.

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