Interaction of Physical Workload and Information Presentation Modality on Cognitive Inhibition Performance

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Studies of the effect of physical workload on cognitive task performance have yielded conflicting results. Some experiments indicate cognitive performance peaks with moderate physical loading while others suggest a strictly negative effect of any level of physical exertion on cognition. Despite a large body of research, very little work has investigated the interaction effect of physical load and modality of information presentation on cognitive task performance. In the present experiment, 24 highly fit young males performed a stop-signal task in which the stimuli were coded visually or aurally while simultaneously running at one of three levels of exertion (0%, 50%, and 70% VO_2max). Results showed that inhibition accuracy was higher for the auditory stimuli than for the visual stimuli, but inhibition times (derived from response times and delay times) were shorter for visual stimuli than for auditory stimuli. There was no significant effect of exertion level on cognitive inhibition performance likely due to participant fitness level. Overall, results show that highly fit young males produce high inhibition performance across modalities of information presentation even under high physical loads.

Practitioner Summary: Auditory information presentation under physical load extends response time but may promote inhibition accuracy. Visual information presentation promotes response time with concurrent physical workload. Cognitive inhibition performance by highly fit males does not appear to degrade under physical loads up to 70% of maximal oxygen uptake. Results may be useful for occupations requiring simultaneous physical and cognitive performance, such as soldiers, police, etc.

Keywords: Multitasking, Physical Exertion, Cognitive Performance, Multimodality

1 Introduction

Many occupations require workers to perform cognitive tasks while concurrently under physical workload, including firefighters navigating a burning building while carrying a victim. Studies of the effect of physical workload on cognitive task performance have yielded conflicting results, with some claiming a potential benefit to moderate levels of physical exertion while others state there is only a detrimental effect. Furthermore, despite a large body of research, very little work in the field has investigated the interaction between physical load and modality of information presentation on cognitive task performance. In order to improve performance of operators in occupations involving high multitasking demands, it is important to know how physical workload influences cognitive task performance and whether modality of information presentation might mitigate any negative effects.

1.1 Effect of Physical Loading on Cognitive Task Performance

In the extensive body of research on the effect of physical exertion on cognitive task performance, two main trends have emerged: (1) an “inverted U” trend indicating that moderate physical exertion levels facilitate cognition compared to lower and higher levels; and (2) a decreasing trend indicating that any level of physical exertion is detrimental to cognition. Related to the “inverted U” trend, Reilly and Smith (1984) found an optimal zone of performance between 40% and 55% VO_2max, a measure of maximal volumetric oxygen uptake in an individual. Similarly, a later study (Reilly and Smith, 1986) found that peak performance in a simple tracking task occurred at 38% of VO_2max. In a later study, Chang and Etnier (2009) found that a 45-minute bout of moderate-intensity resistance training improved both lower-level and higher-level cognitive processes in middle-aged adults. Similarly, Mehta, Nussbaum, and Agnew (2012) reported an “inverted U” trend for the effect of localized muscle exertion on a mental arithmetic task. Finally, in a review of the literature, Brisswalter, Collardeau, and Rene (2002) concluded that there exists an optimal zone of exercise intensity that increases performance in cognitive tasks, and that level is moderate to heavy.

Contrary to the findings above, a review conducted by Tomporowski (2003) concluded that acute bouts of treadmill running led to impaired cognitive performance during the running task, but facilitated cognitive performance after completion of the exercise. Tomporowski also concluded that moderate intensity and moderate duration physical workload benefit long-term memory performance, but no other aspects of cognition. Similarly, a meta-analysis performed by Lambourne and Tomporowski (2010) concluded that cycling was associated with enhanced performance both during and after exercise. However, treadmill running led to degraded performance during exercise and a small improvement following exercise.

In summary, the findings regarding the effect of physical exertion on cognitive performance are mixed. Related to the seemingly competing results in the literature, Chang et al. (2012) concluded in their meta-analysis that the findings of each experiment are highly dependent on the paradigms used—the cognitive task, specific exercise type, exercise intensity, duration of the exercise period, and the timing of cognitive task administration (e.g., during exercise, after exercise, etc.). Therefore, it is possible that there is limited generalizability across all combinations of experimental paradigms.

1.2 Human Performance in Multimodal Interfaces

Another topic for which there is an extensive base of literature is the information processing effect of presenting perceptuo-cognitive task stimuli via different modalities (e.g., visual, auditory, haptic). For example, several studies have demonstrated that choice response time is generally shorter for auditory stimuli than for visual stimuli (e.g., Niemi, 1978; Green and von Gierke, 1983). However, in an experiment performed by Yagi et al. (1999), they reported that response times to visual stimuli were significantly shorter than response times to auditory stimuli when under moderate aerobic exercise; this difference was non-existent in non-exercise conditions. Related to this, in the cognitive science literature, Cowan's (1988) model of human information processing indicates that the visual sensory store lasts only a few hundred milliseconds while the auditory sensory store lasts several seconds, suggesting that the processing time of auditory stimuli should take longer than the processing of visual stimuli. Beyond single modality information presentation, research has found that multimodal interfaces support potential performance benefits. Hecht et al. (2006) found that response time to a trimodal stimulus consisting of visual, auditory and haptic components was shorter than for any combination of bimodal stimuli, which in turn were shorter than for any unimodal stimuli.

1.3 Motivation

As identified in the literature review, there is a corpus of work that has investigated the interaction between physical load and cognitive task performance. There is also a body of work that has examined human performance when exposed to stimuli via different and multiple modalities. However, there is very little work examining differences in how people, operating under physical workload, respond to stimuli presented via auditory and/or visual modalities. It is possible that presentation of information in one or multiple modalities may mitigate any potential degrading effects of physical exertion on cognitive task performance. The present study was conducted to determine whether there is an interaction effect of physical loading and modality of information presentation on concurrent cognitive task performance.

2 Method

2.1 Participants

Twenty-four highly fit males between the ages of 18 and 25 (20.75±2.17 years) were recruited for participation in the experiment. Fourteen participants were recruited from the Reserve Officer Training Corps (ROTC) program and the remaining ten were required to (1) report a two-mile running time that was fast enough to pass the United States Army Physical Fitness Test (APFT), (2) pass the push-up portion of the APFT, and (3) pass the sit-up portion of the APFT. Chang et al. (2012) concluded that participant physical fitness was a significant moderator in results investigating the effect of physical exertion on cognitive task performance, so we recruited as uniform a group as possible in terms of fitness level. The effectiveness of this recruiting approach was confirmed by our analyses (described below), which indicated no significant differences between the two groups for either of the responses recorded during the experiment.

2.2 Apparatus and Scenario

2.2.1 Virtual Reality Locomotion Interface

A virtual reality locomotion interface (VRLI) setup was used for the study, including a Biodex RTM 400 rehabilitation treadmill positioned in front of a Draper (10' x 10') rear-projection screen and surrounded by a wooden canopy suspending a linemen's safety harness. Participants donned the safety harness during test trials in order to ensure they would not fall while running on the treadmill and paying attention to a cognitive task. The participants also wore StereoGraphics active light shutter goggles to view a 3D virtual locomotion environment (VLE) as presented on the projection screen. Two projectors were used in the setup, including: one to project the VLE and one to project the cognitive task onto the same screen. The VLE displayed a first-person view of a participant running down an empty street in a suburban town. The cognitive task involved presentation of stimuli from the stop-signal paradigm (Verbruggen, Logan, and Stevens, 2008) described below. The overall VRLI setup was validated for locomotion research by Sheik-Nainar and Kaber (2007).

2.2.2 Stop Signal Task

The stop-signal task (SST) is a simple cognitive task that measures a person's ability to inhibit a response (Verbruggen, Logan, and Stevens, 2008). A participant is first presented with a left or right arrow stimulus and then asked to respond to the arrow as quickly as possible by pressing a corresponding button on a hand-held interface control (similar to a choice reaction time task). In 25% of the trials, a "stop signal" stimulus is presented to the participant following a variable amount of time (referred to as the "delay time"). The stop signal indicates that the participant should inhibit his response and not press any of the buttons on the hand-held device. The default delay time for the stop-signal is 250 ms and decreases by 50 ms if a participant incorrectly responds to the stimulus or is otherwise increased by 50 ms if the participant responds correctly. The next left/right arrow is then presented 4500 ms later, regardless of the participant response time to the stop-signal, such that participants are continually presented stimuli throughout each running trial.

2.3 Independent Variables and Experiment Design

Three independent variables were manipulated in the experiment, including physical exertion level, SST arrow modality, and SST stop signal modality. Since Reilly and Smith (1984) found an optimal range of physical exertion on cognitive task performance between 40% and 55% of VO_2max, we chose one level below, one within, and one above that range for our test purposes. The exertion level was manipulated as a between-subjects variable, with a 0% VO_2max (i.e., standing still) group, a 50% VO_2max group, and a 70% VO_2max group. It was expected that the sample recruited for participation would have uniformly high fitness levels, so we calculated a treadmill speed corresponding to these exertion levels using a mean VO_2max of 59.2 ml/kg*min (SD = 0.7 ml/kg*min), as reported by Swain et al. (1994) for highly fit males. These levels corresponded to 0 mph, 4.9 mph, and 7.1 mph, respectively, for the highly fit male population used in the experiment, and the same speed was used for all participants within each exertion-level group. Regarding the SST variables, the arrow stimulus modality was manipulated as visual or auditory and the stop signal modality had the same settings. Both were manipulated as within-subject variables and fully-crossed in the experiment design, resulting in the four scenarios presented in Table **1**. Consequently, each participant participated in four jogging sessions, with each session presenting one of the four combinations in Table **1**. The order of administration of the scenarios was randomized for all participants.

Table 1. Combinations of arrow and stop signal modalities in the SST

Combination	Arrow Modality	Stop Signal Modality
1	Visual: White Left or Right Arrow	Visual: Red Text Displaying "STOP"
2	Visual: White Left or Right Arrow	Auditory: 75 ms Beep (750 Hz)
3	Auditory: Voice Saying "Left" or "Right"	Visual: Red Text Displaying "STOP"
4	Auditory: Voice Saying "Left" or "Right"	Auditory: 75 ms Beep (750 Hz)

2.4 Dependent Variables

Two dependent variables were collected as part of the study, including inhibition accuracy and stop signal reaction time (SSRT). Inhibition accuracy was calculated as the total number of correct inhibitions divided by the total number of instances in which a stop signal was presented to the participant (i.e., the calculation did not include trials that did not contain a stop signal). SSRT is a measure of the time it takes for a participant to inhibit a response. Since this cannot be calculated directly (because the participant is supposed to be inhibiting the response), the SSRT was derived by subtracting each participant's average delay time from his average response time to trials not requiring inhibition of the response (see Verbruggen, Logan, and Stevens, 2008).

2.5 Hypotheses

Based on the findings by Reilly and Smith (1984, 1986) and Brisswalter, Collardeau, and Rene (2002), it was expected that a moderate exertion level (50%) would increase inhibition accuracy (Hypothesis 1) and decrease SSRT (Hypothesis 2) in the SST. Furthermore, based on the results reported by Yagi et al. (1999), it was expected that visual stimuli (e.g., SST arrows and stop signals texts) would facilitate higher inhibition accuracy (Hypothesis 3) and shorter SSRT (Hypothesis 4) than SST trials containing multiple-modality stimuli (e.g., visual arrow and auditory stop signal), followed by SST trials containing only auditory stimuli.

2.6 Procedure

All participants were initially asked to read and sign an informed consent form and a demographic questionnaire. If the participant was not part of the ROTC program, he was asked to report 2-mile run time, and perform the push-up and sit-up portions of the APFT. (The non-ROTC participants were given a 5-minute break before beginning the experiment.) All participants were required to complete a baseline simulator sickness questionnaire (SSQ; Kennedy et al., 1993). Subsequently, they completed a 3-minute training session on the SST, including how to respond to the arrows and how to inhibit responses when presented with a stop signal.

After the SST training, participants began the actual experiment trials. Before each trial, participants were given a 1-minute modality familiarization session on the modality combination of the SST in the upcoming trial (e.g., if the upcoming modality combination was visual arrows and visual stop signals, then the participants were administered a 1-minute familiarization session using these settings). Subsequently, the treadmill was set to the speed corresponding to the participant's assigned exertion level and he began running. After 3 minutes (i.e., enough time for the participant to reach steady-state heart rate/oxygen consumption; Astrand and Rodahl, 1986), the SST was presented and lasted for approximately 5 minutes. At the end of the SST, the participant adjusted the treadmill speed to 0 mph (if not in the 0% group), exited the VRLI setup, and completed a SSQ. He was then given up to 6.5 minutes of rest before beginning the next trial. This procedure, starting from the modality familiarization step, was repeated three more times, one for each of the remaining combinations SST arrow and stop signal modalities. In total, the experiment lasted 75-90 minutes and participants were compensated at a rate of $15/hour.

2.7 Data Analysis

All dependent variables were analyzed with a split-plot analysis of variance (ANOVA) where exertion level was the whole-plot factor and participant (nested within exertion level) was used as the whole-plot error term. Military status was screened as a whole-plot factor and found to be insignificant in effect on both response variables (likely due to the comparable fitness level of the non-military participants); consequently, this term was removed from all subsequent analyses. The split-plot factors included arrow modality, stop signal modality, and all two-way and three-way interactions. Trial number, which represented the order in which the modality combinations were presented to each participant, was screened as a split-plot factor and was also found to be insignificant in effect on either response measure; consequently, it was removed from the analyses. The experiment data were aggregated to produce one observation for each participant under each combination of arrow modality and stop signal modality (i.e., four observations, in total, for each participant). Both inhibition accuracy and SSRT met ANOVA assumptions of constant variance and residual normality.

3 Results

3.1 Inhibition Accuracy

An ANOVA was performed on the inhibition accuracy response and revealed a significant effect of the initial/arrow stimulus modality ($F(1,54)=11.795$, $p=0.001$). All other main effects and interactions were insignificant at the α=0.05 significance level. As presented in Figure **1**, participants were more accurate inhibiting their responses when exposed to an auditory stimulus versus the visual left and right arrows.

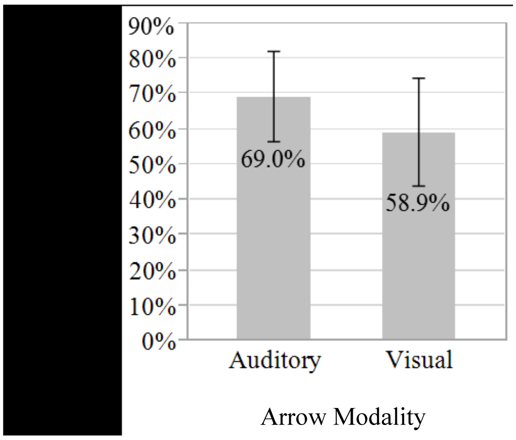

Figure 1. The effect of arrow modality on mean inhibition accuracy (error bars represent one standard deviation).

3.2 Stop-Signal Reaction Time

An ANOVA on the SSRT also revealed a significant main effect of the initial/arrow stimulus modality ($F(1,54)=14.066$, $p<0.001$). No other main effects or interactions were significant. As shown in Figure **2**, on average, participants took longer to inhibit their responses with auditory/verbal presentation of the words “left” or “right” as compared to when the left and right arrows appeared on the screen in front of them.

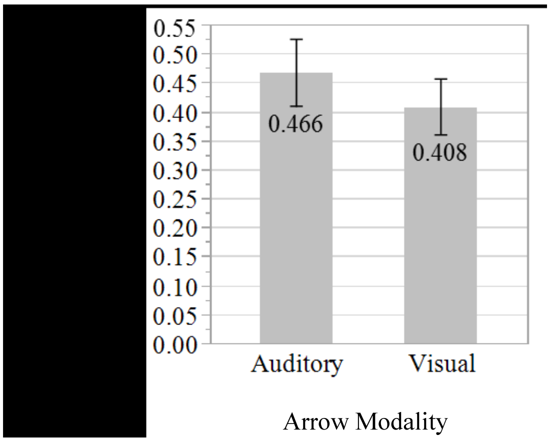

Figure 2. The effect of arrow modality on mean SSRT (error bars represent one standard deviation).

4 Discussion

Hypotheses 1 and 2 posited that inhibition accuracy would increase and SSRT would be shorter for the 50% VO_2max group as compared with the 0% and 70% VO_2max groups, respectively. The lack of a significant effect of exertion level on either response refuted both hypotheses. It is possible that the 70% VO_2max exertion level was not high enough to cause a significant physiological response (e.g., adrenaline concentration in the blood, increased blood flow, etc.) due to the very high fitness level of all of the participants. The physical tasks likely did not require attentional and metabolic resources that would normally be allocated to the cognitive task, as suggested by Audiffren, Tomporowski, and Zagrodnik (2009). Chang et al. (2012) also suggest that RT either may not be affected by performance or is not a particularly reliable measure of cognitive performance, which could also explain the lack of a significant effect of exertion level on SSRT. Furthermore, these results are in line with the conclusions put forth by Lambourne and Tomporowski (2010), who stated that neurophysiological arousal during exercise may have its greatest impact on basic, bottom-up processes and automatic processing, but have minimal or no effect on higher-level, top-down processes. Inhibition is a complex “executive” cognitive process, so the task was likely complex enough to not be more affected by the physical loading condition.

Regarding the treadmill running task, it is possible that treadmill running may not account for the potential cognitive loading associated with running across rough terrain, as would be expected in a real-world task environment. Real-world running also requires self-pacing, another cognitive element that is not required in treadmill running. Previous research in the area has demonstrated increased cognitive loads associated with running as compared to cycling (Lambourne and Tomporowski, 2010). It is likely that these findings on increased cognitive load extend to over-ground running on changing terrain as compared with treadmill running. Therefore, it is possible that the assessment of the influence of physical workload on cognitive task performance in the present experiment is relatively conservative compared to any effects that might be observed in a comparable real-world task scenario involving cognitive performance while running over terrain.

Hypothesis 3 posited that inhibition accuracy would be highest for conditions containing only visual arrows and stop signals, followed by conditions containing stimuli presented via both modalities, followed by conditions containing only auditory arrows and stop signals. The results refuted this hypothesis as well. Higher inhibition accuracy associated with auditory presentation of the arrow stimuli was actually in line with Cowan’s (1988) model of information processing indicating longer processing of auditory stimuli as compared to visual stimuli. The longer processing time of auditory cues translated to longer reaction times, which likely exceeded the SST “delay time” (i.e., the time between presentation of the arrow and the onset of the stop signal). Thus, participants had more time to inhibit their responses when arrows were presented aurally.

Hypothesis 4 stated that SSRT for visual arrows and stop signals would be shorter than in trials containing a multimodal combination, which would be shorter than those containing auditory arrows and stop signals. Our results partially confirmed this hypothesis, as the SSRT for visual arrows was significantly shorter than the SSRT to auditory presentation of the arrow stimuli. The shorter SSRT to visual signals seemingly confirms our explanation of the results relative to Hypothesis 3 and further agrees with the model put forth by Cowan (1988); that is, increased processing time associated with the auditory arrows (compared to the visual stimuli) and increased time for participants to decide to inhibit any response. This increased processing time was likely longer than the delay time, which increased accuracy in inhibiting responses. Furthermore, the lack of an interaction between the arrow and stop signal modalities suggests that there was no detrimental effect associated with switching between the visual and auditory modalities as compared with exposure to the same modalities of presentation for the arrows and the stop signals.

5 Conclusion

The results of this study indicate that physical loading up to 70% of maximal oxygen uptake has little effect on cognitive inhibition abilities of highly fit males between the ages of 18 and 25 years old. Furthermore, the results confirm a human information-processing model posited by Cowan (1988), which suggests that auditory stimuli take longer to process than visual stimuli. The delay in auditory stimulus processing time may actually increase inhibition task response accuracy dependent upon task conditions. Findings also suggest that there may be no interaction between physical load and modality of information presentation for cognitive inhibition in highly fit males.

5.1 Limitations

As mentioned in the discussion section, it is possible that the treadmill running task did not completely simulate the mental load associated with running overground and self-pacing. For this reason, it is likely that the results of this study represent a conservative assessment of physical load on cognitive task performance. Given the lack of significant effect of exertion level on the responses, it is possible that 70% of VO_2max was not a high enough exertion level to trigger differences in cognitive task performance in the highly fit young males recruited for the experiment. Finally, it is possible that the noise from the treadmill and the sound generated by participant feet hitting the treadmill surface may have influenced performance in the stop-signal task, particularly in conditions that presented auditory stimuli.

5.2 Future Work

Future work should include a larger sample of fit participants working under a broader range of percentages of maximal oxygen uptake in the physical task. Furthermore, future work should look at the effect of longer treadmill runs (e.g., more than 20 minutes) to see if the added running time and potential fatigue has any effect on cognitive inhibition. Future research should also assess a more demanding cognitive task requiring other aspects of cognition, such as decision making or long term memory. Finally, such work should also examine other modalities of information presentation, including presentation of haptic cues while under a physical load and combinations of auditory, visual and haptic cueing.

Acknowledgement

Carl Pankok's and David Kaber's work on this research was supported in part by a grant from the U.S. National Institute for Occupational Safety and Health [grant number NIOSH: No.2 T42 OH008673-13]. The opinions expressed in this report are those of the authors and do not necessarily reflect the views of NIOSH.

References

Astrand, P. and K. Rodahl. 1986. Textbook of Work Physiology: Physiological Bases of Exercise (3rd ed.). New York: McGraw Hill.

Audiffren, M., P. D. Tomporowski, and J. Zagrodnik. 2009. "Acute Aerobic Exercise and Information Processing: Modulation of Executive Control in a Random Number Generation." Acta Psychologica 132: 85-95.

Brisswalter, J., M. Collardeau, and A. Rene. 2002. "Effects of Acute Physical Exercise Characteristics on Cognitive Performance." Sports Medicine 32 (9): 555-566.

Chang, Y. and J. Etnier. 2009. Effects of an Acute Bout of Localized Resistance Exercise on Cognitive Performance in Middle-Aged Adults: A Randomized Controlled Study." Psychology of Sport and Exercise 10: 19-24.

Chang, Y. K., J. D. Labban, J. I. Gapin, and J. L. Etnier. 2012. "The Effects of Acute Exercise on Cognitive Performance: A Meta-Analysis." Brain Research 1453: 87-101.

Cowan, N. 1988. "Evolving Conceptions of Memory Storage, Selective Attention, and Their Mutual Constraints Within the Human Information-Processing System." Psychological Bulletin 104 (2): 163-191.

Green, D.M. and M. von Gierke. 1984. "Visual and Auditory Choice Reaction Times." Acta Psychologica 55: 231-247.

Hecht, D., M. Reiner, and G. Halevy. 2006. "Multimodal Virtual Environments: Response Times, Attention, and Presence." Presence: Teleoperators & Virtual Environments 15 (5): 515-523.

Kennedy, R. S., N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. 1993. "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness." International Journal of Aviation Psychology 3 (3): 203-220.

Lambourne, K. and P. Tomporowski. 2010. "The Effect of Exercise-Induced Arousal on Cognitive Task Performance: A Meta-Regression Analysis." Brain Research 1341: 12-24.

Mehta, R. K., M. A. Nussbaum, and M. J. Agnew. 2012. "Muscle- and Task-Dependent Responses to Concurrent Physical and Mental Workload During Intermittent Static Work." Ergonomics 55 (10): 1166-1179.

Niemi, P. 1978. "Stimulus Intensity Effects on Auditory and Visual Reaction Processes." Acta Psychologica 43: 299-312.

Reilly, T. and D. Smith. 1984. "Influence of Metabolic Loading on a Cognitive Task." Megaw (Ed.), Contemporary Ergonomics, 104-109.

Reilly, T. and D. Smith. 1986. "Effect of Work Intensity on Performance in a Psychomotor Task During Exercise." Ergonomics 29 (4): 601-606.

Sheik-Nainar, M. A. and D. B. Kaber. 2007. "The Utility of a Virtual Reality Locomotion Interface for Studying Gait Behavior." Human Factors 49 (4): 696-709.

Swain, D. P., K. S. Abernathy, C. S. Smith, S. J. Lee, and S. A. Bunn. 1994. "Target Heart Rates for the Development of Cardiorespiratory Fitness." Medicine and Science in Sports and Exercise 26 (1): 112-116.

Tomporowski, P. D. 2003. "Effects of Acute Bouts of Exercise on Cognition." Acta Psychologica 112: 297-324.

Verbruggen, F., G. D. Logan, and M. A. Stevens. 2008. "STOP-IT: Windows Executable Software for the Stop-Signal Paradigm." Behavior Research Methods 40: 479-483.

Yagi, Y., K. Coburn, K. Estes, and J. Arruda. 1999. "Effects of Aerobic Exercise and Gender on Visual and Auditory P300, Reaction Time, and Accuracy." European Journal of Applied Physiology 80 (5): 402-408.