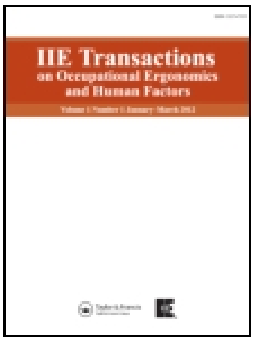

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The Effect of Physical Workload and Modality of Information Presentation on Cognitive Inhibition in High-Fit Young Males

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Occupational Applications

This study presents an experiment assessing the interaction between physical task load and modality of information presentation on cognitive task performance. Results indicated that males of equivalent high fitness, between the ages of 18 and 25, can perform complex cognitive tasks reliably well while performing a concurrent physical task requiring up to 70% of aerobic capacity. Furthermore, results revealed that participants respond slightly more quickly to visual stimuli than auditory stimuli, but are equally adept at inhibiting responses presented via either modality. These results are applicable to the design of information displays for information processing tasks as part of occupations requiring simultaneous worker physical performance, such as soldiers in combat situations, firefighters in emergency rescue, police officers in security patrols on foot, etc.

Technical Abstract

Background: Many occupations require workers to perform cognitive tasks while concurrently performing a physical task, such as a soldier taking orders while running to a helicopter evacuation point or a firefighter navigating through a burning building. Diverse personal factors have been identified to influence the effect of physical workload on cognitive performance; however, the literature presents some contradictions and findings appear heavily dependent on participant sample characteristics, physical task type, and cognitive task type. ***Purpose***: To assess the interaction between physical workload and modality of information presentation on performance of a concurrent cognitive task by highly fit young males. ***Methods***: Twenty-four highly fit males between the ages of 18 and 25 completed the experiment. Participants ran on a treadmill at one of three physical exertion levels (0, 50 and 70% VO_2max). Levels were selected based on a previously-defined "optimal range" of 40-55% VO_2max for facilitating concurrent cognitive performance. Participants were exposed to exertion below, within, or above the optimal range for 8 minutes in each trial while concurrently performing a stop-signal task with stimuli presented either visually or aurally. Accuracy, response time, stop-signal reaction time, and perceived cognitive workload were recorded. ***Results***: Physical exertion level did not appear to have a significant effect on responses with the exception of a decrease in accuracy that approached significance ($p<0.10$). Stimulus modality had a significant effect, with higher accuracy, lower response time, and lower stop-signal reaction time occurring with visual stimuli compared to auditory. The modality of the stop-signal (an indicator that participants should inhibit a reaction) had no effect on any response. No significant interaction was found between physical exertion level and modality of information presentation on cognitive inhibition.

Conclusions: Highly fit young males, when subjected to an acute bout of exercise requiring 70% VO_2max or less and lasting 8 minutes or less, exhibit no negative effects on cognitive inhibition performance, but response time appears faster with visual vs. auditory stimuli.

Keywords

Multitasking; Physical Exertion; Cognitive Performance; Multi-modal displays

Introduction

Many occupations requiring physical exertion also place concurrent demands on human mental or cognitive resources. Some examples include operators of manufacturing systems, security officers on patrol, soldiers in combat operations, and emergency response or rescue team operations (Mozrall & Drury, 1996). These jobs also present information to operators across multiple sensory modalities. In order to improve operator performance in such occupations, it is important to know how physical workload influences cognitive task performance and whether the modality of information presentation might mitigate any negative effects associated with physical loading.

Link between Physical Workload and Cognitive Task Performance

In two experiments, Reilly and Smith investigated the effect of physical work intensity on performance of an arithmetic task (Reilly and Smith, 1984) and in a pursuit-rotor tracking task in which participants were asked to follow a small disc on a rotating table (Reilly and Smith, 1986). Both experiments used the same participant sample, including ten fit males subjected to six percentages of maximal oxygen uptake (VO_2max) ranging from 0% to 85% of the participants' VO_2max. Performance on both tasks approximated an “inverted U” trend. In the pursuit-rotor task, the optimal performance occurred at a physical load of 38% of VO_2max, where the percentage of VO_2max represents different physical exertion levels. (In general, as physical workload increases, oxygen uptake increases until it reaches VO_2max (Tayyari and Smith, 1997).) Reilly and Smith’s (1984) research revealed slightly different results on performance in the arithmetic task, where optimal cognitive performance occurred at a physical load of 44% of

VO_2max. They also found also an optimal “zone” of physical workload, ranging from 40% to 55% VO_2max for facilitating cognitive performance. It is likely that the nature of the two cognitive tasks (arithmetic vs. pursuit tracking) led to the differences in results, as the task manipulation was the only independent variable in the two studies.

In a review of related literature, Brisswalter et al. (2002) investigated the effects of physical task characteristics, including exercise intensity, physical fitness, exercise duration, and physical task complexity on cognitive task performance. They also concluded that there exists an optimal zone of exercise intensity (moderate to heavy), which improves cognitive performance in decision tasks. Chang and Etnier (2009) investigated the effect of physical task duration and intensity on cognitive performance. Their study, which focused on middle-aged adults, showed that a 45 min bout of moderate-intensity resistance exercise improved both lower-level and higher-level cognitive processes. More recent studies have investigated the relationship between localized muscle exertion and cognitive performance. For example, Mehta et al. (2012) investigated the effect of physical workload on cognitive task performance during shoulder abduction, and wrist and torso extension. They also found an inverted U-shape curve for a mental arithmetic task with the lowest performance occurring at a higher physical workload level (65% of maximum voluntary contraction). In a similar study, Mehta and Agnew (2013) found that performance in a mental arithmetic task increased with shoulder muscle contractions (during abduction) that were 30% and 50% of maximal voluntary contraction (MVC) as compared to a 15% MVC condition. The results provide further evidence that there may be a moderate range of exertion for which cognitive performance increases.

Another influential factor in the effect of physical workload on cognitive task performance is the timing of the cognitive task relative to the start, end, and/or duration of the concurrent physical task. With respect to the evolution of performance over time, Audiffren et al. (2009) found that decrements in cognitive task performance occurred during the first few minutes of an exercise session when a high physical demand was placed on participants before they reached an aerobic steady state. Furthermore, there appeared to be no difference in cognitive task strategy during the different phases of the physical work bout, including the recovery period. Similarly, Lambourne and Tomporowski (2010) reviewed studies related to the effect of acute exercise on young adult cognition during and after bouts of exercise. They found that acute bouts of exercise significantly degraded cognitive functioning, which was in-line with an earlier review by Tomporowski (2003). Lambourne and Tomporowski (2010) also found that treadmill running led to impaired cognitive performance, but a small improvement occurred after the exercise. Similarly, Labban and Etnier (2011) reported that performance in a long-term memory task was improved more after a bout of acute exercise than after no exercise. They also found that exercise intensity and duration are important factors that can influence cognitive performance and showed that moderate intensity and duration of physical exercise has a beneficial effect on long-term memory.

Regarding the duration and type of physical task, Tomporowski (2003) revealed that the effect of exercise on cognitive processing depends on the type and duration of the physical task. It was found that moderate levels of aerobic, steady-state exercise facilitated specific stages of information processing. Based on the review, physical exertion facilitates performance on some cognitive tasks under certain circumstances, but it can also impair performance on other tasks or on the same tasks under different conditions. Physical tasks that have been previously studied for the effect of physical exertion on cognitive performance include cycling, treadmill jogging, and running at moderate and high speeds. Several studies have tested a 0% exertion level as a control condition for comparison with the higher-intensity exercise conditions. Some of the studies that we reviewed found that performing a cognitive task during treadmill running facilitates cognitive performance (e.g., Hancock and McNaughton, 1986) while other studies found that treadmill running at progressively higher heart rates produces a U-shaped facilitation effect on cognitive performance (e.g. Levitt and Gutin, 1971).

Visual and Auditory Sensory Modalities

Some research has been conducted on the integration and interaction of visual and auditory perceptual systems in single and multitask scenarios. In Cowan’s (1988) model of human information processing, there are modality-specific sensory stores to facilitate the perceptual process. A visual sensory store is identified with the persistence of a few hundred milliseconds along with an auditory sensory store persisting for several seconds. These sensory stores suggest that auditory signals may require longer coding and processing time or that more auditory information can be stored at any time. Kohlrausch and van de Par (1999) identified substantial differences in human ability to detect asynchrony in auditory and visual stimuli with the audio stimulus leading vs. lagging the visual stimulus. Based on their study, Kohlrausch and van de Par concluded that attentional resources for processing auditory and visual stimuli are not completely independent. Also, they found that identification of a stimulus in one modality did not impair ability to identify a concurrent stimulus via another. In another study, Rauterberg (1998) investigated the effect of use of auditory feedback in a human-machine interface on performance of plant operators. The author observed a significant improvement with auditory alarms compared to visual-only feedback. Results suggested that the auditory modality was attention-demanding but allowed for breaks in operator visual attention, reducing workload. However, the auditory modality provides poor referability; sound patterns cannot be referred to on an interface at a user’s convenience, like visual cues. Rauterberg mentioned that visual patterns offer good referability because information can be stored. Finally, Hecht et al. (2006) investigated underlying cognitive mechanisms in a multimodal virtual environment that created an enhanced sense of presence. They asked participants to respond to different stimulus modalities by pressing a button on a stylus. Results revealed that reaction time under a trimodal condition (visual, auditory and haptic stimuli) was shorter than all three bimodal combinations and any unimodal condition.

The Stop-signal Task

The ability to inhibit inappropriate or irrelevant responses to environmental stimuli is a primary function of executive cognitive control (Verbruggen et al., 2008). Inhibiting a stimulus-response association can be critical under certain circumstances in a variety of occupations. For example, a forklift operator may be required to inhibit action in lifting a load if (s)he notices the load is unstable; an assembly line worker, primed to perform the same set of actions each time a workpiece arrives, may be required to inhibit automatic actions if a defect is noticed in a part; or an airline pilot may abort a landing if (s)he notices the rate of aircraft descent is too fast. Sometimes, occupations require the ability to inhibit a cognitive response while concurrently under physical workload, such as a police officer holstering a weapon, firefighter re-direction in attempting to exit a burning building due to a sudden obstruction of path, or a machine operator in an industrial process inhibiting press of a start button due to an emergency situation. It has been demonstrated that the inability to inhibit responses may lead to friendly fire in a military context (Wilson, Head, and Helton, 2013; Wilson et al., 2014). The stop-signal paradigm is currently one of the most popular tasks for examining response inhibition in laboratory investigations (Verbruggen et al., 2013). Stop-signal reaction time (SSRT) is the time for successful response inhibition and has proven to be a useful indicator of cognitive control (Verbruggen et al., 2008). Padilla et al., (2013) compared performance of physically active and passive young participants in “strategic” and “standard” versions of the stop-signal task (SST). In the “strategic” task, participants were instructed to prioritize speed over accuracy; whereas, in the “standard” version, they were told to prioritize accuracy, allowing for a more conservative approach to the task. They found participants who led an active lifestyle to be more efficient in inhibiting a response in the strategic task than participants with a sedentary lifestyle, but there was no difference in the standard version. In other studies, Boehler et al. (2012) and Boehler et al. (2014) used modified versions of the SST to demonstrate cancellation of a motor response to be accelerated if successful inhibition was rewarded. In a more recent study, Gan et al. (2014) measured inhibitory control in an experiment where 50 young adults performed the SST under the influence of alcohol and with a placebo. They found inhibitory control was significantly decreased under the influence of alcohol compared to the placebo condition.

Motivation

Given that we do not experience our environment via a single modality, the purpose of the current study was to investigate the effect of physical workload on concurrent cognitive task performance with different modalities of information presentation. As described in the following subsections, physical load was manipulated via a treadmill-jogging task. This task was chosen for study as it approximates over-ground jogging, a physical task that is common among occupations requiring concurrent cognitive task performance under physical workload (e.g., soldiers, firefighters, rescue teams, etc.). It should be noted that the same occupations may also, on occasion, require workers to maintain a standing posture while monitoring a situation; for example, a fire chief monitoring the activity of a team of operators attempting to control a fire. Furthermore, jogging and standing postures have been used extensively in previous work to manipulate physical load during cognitive task performance (see Tomporowski, 2003), providing further justification for use of these conditions in the present study. There is no existing research examining the interaction between stimulus presentation modality and concurrent physical load in a multitasking scenario. Furthermore, given the differential effects of physical workload on cognitive task performance, we investigated multiple levels of physical workload.

Hypotheses

Based on the findings by Kohlrausch and van de Par (1999) and Cowan (1988), we hypothesized that visual encoding of cognitive task stimuli (initial and inhibitory) would produce lower response accuracy (Hypothesis 1; H1), faster response time in trials not requiring response inhibition (“go-signal” trials; H2), lower SSRT (H3), and lower subjective perceptions of mental workload (H4) in a stop-signal task than for trials in which the signals were encoded auditorally. With respect to the physical workload manipulation, we expected higher response accuracy (H5), lower response time in go-signal trials (H6), lower SSRT (H7), and lower cognitive workload ratings (H8) for moderate physical workload, followed by low exertion and then high exertion. The expected benefit of moderate-intensity exercise was based on the findings of Reilly and

Smith (1984) and Brisswalter et al. (2002). We anticipated the effects of the high-intensity physical exertion to be similar to the effects of alcohol on SST performance, as reported by Gan et al. (2014); i.e., performance would significantly decrease. Although no existing work has investigated the interaction between physical exertion and modality of information presentation, we expected that our hypotheses regarding information presentation modality (H1-H4) would be exaggerated under moderate physical loading compared to high and low levels of physical loading (H9).

Method

Participants

Twenty-four highly fit males between 18 and 25 years of age (M = 20.75 years, SD = 2.17 years) participated in the experiment with a mean height of 1.80 m (SD = 0.08 m) and a mean body mass of 77.68 kg (SD = 8.81 kg). Previous studies showed that fitness level was a significant moderator of effects of exercise on cognitive performance (e.g., Chang et al. 2012), so we recruited highly fit males for a conservative assessment of physical workload and modality of cognitive task presentation effects on cognitive performance. Fourteen of the participants were from the Reserve Officer Training Corps (ROTC) at North Carolina State University. The remaining 10 participants were non-military males whose fitness was validated by passing the push-up and sit-up portions of the United States Army Physical Fitness Test (APFT) as well as confirmation that they could pass the running portion of the test. All participants had normal or corrected 20/20 vision, which was required for performance of the SST. The data collected from one military participant and one non-military participant were excluded due to failure to follow experiment instructions and symptoms of simulator sickness, respectively. Participants were compensated at a rate of $15 per hour for their time. The North Carolina State University Institutional Review Board approved the experimental procedures.

Apparatus

Virtual Reality Locomotion Interface (VRLI)

The VRLI setup used for this study consisted of a Biodex RTM 400 rehabilitation treadmill, a Dell graphics workstation running a custom virtual locomotion environment (VLE) simulation, an InFocus 3D stereoscopic projector, and a Draper (3.05 m x 3.05 m) rear-projection screen (shown in Figure 1). The VLE was presented on the projection screen and participants donned a pair of StereoGraphics 3D goggles in order to view the imagery with binocular disparity cues. The VLE was a simple simulation of a first-person view of jogging through an empty street (i.e., the participant was not looking at a simulated avatar of himself), the speed for which corresponded to the participant's treadmill running speed. A near-identical setup was previously validated for locomotion research by Sheik-Nainar and Kaber (2007).

Stop-signal Task

A modified version of STOP-IT (Verbruggen et al., 2008), a software version of the SST, was developed to investigate the effect of multiple modalities of stimulus presentation. In the SST, participants were presented with an initial stimulus (e.g., a left or right arrow) and instructed to respond as quickly as possible by pressing a directional button on a hand control corresponding to the stimulus. The stimulus remained on the screen until the participant responded, or until 1,250 ms (the maximal reaction time) had elapsed. The default inter-stimulus interval was 4,500 ms and was independent of reaction time. In 25% of the trials, a “stop-signal” was presented directly after a variable amount of time (referred to as the “delay time”). The signal indicated that the participant should inhibit his response to a go-signal. The delay time, initially set at 250 ms, increased by 50 ms in the next trial if the participant correctly inhibited his response, or decreased by 50 ms if the participant incorrectly responded by pressing one of the buttons. A timeline for a single iteration of the SST is depicted in Figure 2.

In the default version of STOP-IT, all stimuli are visual stimuli and all stop-signals are auditory beeps. The modified version used in the present experiment was developed to deliver two types of go-signals and two types of stop-signals, corresponding to the visual and auditory modalities, resulting in four total combinations of information presentation modalities (see Table 1). The auditory stimuli were presented through speakers pointed at the treadmill with a measured intensity of approximately 95 dB, which was at least 10 dB higher than the noise level generated by participants running on the treadmill (approximately 85 dB under the most intense running condition). This difference exceeds the United States Occupational Safety and Health Administration (OSHA) and National Fire Protection Association (NFPA) recommendations for auditory alerts/alarm design, which state that alarms should be 5 dB louder than any ambient noise that lasts longer than 60 sec. Furthermore, a 10 dB increase in sound pressure is perceived as a doubling of intensity/volume among humans. The SST was presented on the same large rear-projection screen as the VLE jogging simulation by using a second LCD projector. Participants were asked to respond to the go-signal by pressing left/right buttons on a presentation pointer control that they held while jogging or standing. All settings of the SST (e.g., changes in delay times, time between trials, etc.) were based on settings for the default version of STOP-IT documented in Verbruggen et al. (2008).

Independent Variables

The independent variables investigated included physical exertion level, stimulus modality, and stop-signal modality. The levels of physical exertion included 0%, 50% and 70% of VO_2max. As reviewed previously, some research identified a range of physical exertion intensity within which cognitive task performance improved and outside of which performance was impaired (e.g., Reilly and Smith, 1984; Brisswalter et al., 2002). The VO_2max levels of the present experiment were chosen such that one level was below, one level was within, and one level was above the identified optimal range of 40%-55% VO_2max. Swain et al. (1994) found the mean (SD) VO_2max for high fit males to be 59.2 (0.7) ml/kg.min. We used this descriptive information to estimate submaximal high fit male VO_2 for 50% and 70% of aerobic capacity. These estimates were used along with Equation 1, from Glass and Dwyer (2007), in order to determine treadmill speeds corresponding to the three exertion levels of the study (0, 50 and 70%), including 0, 7.86 and 11.43 km/h, respectively.

VO_2 (ml/kg.min) = 0.2 (speed (m/min)) + 3.5 (1)

The levels of the initial SST stimulus modality included visual and auditory signals. The levels of the stop-signal modality were also visual and auditory (as shown in Table 1). The specifics of these modalities (e.g., verbal vs. spatial) were chosen based on multiple resource theory of divided attention (Wickens, 1984) in order to cause minimal interference among stimuli from an attentional perspective.

Experiment Design

The experiment followed 3×4 mixed factor design with three levels of physical exertion (0%, 50% and 70%) and the four combinations of initial stimulus and stop-signal modalities (AA, VA, AV, VV). Physical exertion level was manipulated as a between-subject factor since participant fatigue was expected during the experiment, particularly for the moderate or high-intensity exercise conditions. We designed the experiment to limit as much as possible fitness and fatigue effects on test results. Physical exertion levels were randomly assigned to the participants. Initial stimulus and stop-signal modalities were tested as within-subject factors. The sequence in which each participant was presented the four modality combinations was randomized in order to mitigate potential trial order effects, including learning effects or fatigue creep.

Procedure

Prior to the scheduled experiment time, non-military participants were asked to estimate how much time it would take for them to run 3.22 km (2 mi). If their self-reported time met the APFT requirements for their age group, they were scheduled for participation in the experiment. Upon arrival at the laboratory, participants read and signed an informed consent document, a demographic questionnaire asking for general information about their background, and a baseline Simulator Sickness Questionnaire (SSQ; Kennedy et al., 1993). If the participant was a non-military participant, he was asked to complete the push-up and sit-up portions of the APFT before being allowed to continue the experiment. Non-military participants were subsequently given 4-5 minutes of rest before beginning the training portion of the experiment. Tayyari and Smith (1997) state that 1-2 minutes of rest from an intense work bout allows for 80-90%

recovery in terms of fatigue (as indicated by lactic acid levels). Consequently, the rest period was considered sufficient for the non-military participants to recover before beginning the experiment.

Participants entered the VRLI and were asked to don a safety harness in order to prevent falling during running on the treadmill. Participants who were exposed to the 0% exertion level were also asked to wear a safety harness for consistency with the two jogging groups. A 3-minute familiarization session was first provided to familiarize the participant with the SST, including what to do when a stimulus and/or a stop-signal was presented. Once comfortable with the SST, participants were given a 1-minute training session corresponding to the modality combination being tested in the upcoming block of experimental trials. Each of the four blocks presented the participant with one combination of the crossing of stimulus and stop signal modalities (2 stimuli x 2 stop-signals = 4 total blocks). For example, if the upcoming block of trials consisted of visual stimuli and visual stop-signals, then the one-minute training session consisted of visual stimuli and visual stop-signals. Participants were required to stand but not to run during the 1-minute training session.

Following the training session, if the participant was required to jog, the treadmill was set to the desired speed and after 3 minutes (i.e., when the participant reached steady state heart rate/oxygen consumption; Astrand and Rodahl, 1986), the SST was started. Iterations of the SST shown in Figure 2 were presented continuously to the participant until the end of the 8-minute jog, at which time the treadmill was stopped. The participant was subsequently given a workload rating form and a post-trial SSQ to complete.

The participant was allowed to rest for 5.5 or 6.5 minutes based on his physical exertion level (Astrand and Rodahl, 1986). The rest period calculation was based on the level of energy expenditure for each physical exertion level and using Murrel's (1965) equation for total recovery time required during a work shift. If the participant exhibited any symptoms of simulator sickness, he was allowed to rest longer until he felt well enough to continue the experiment. The procedure was the same for participants who were exposed to the 0% exertion level, except that they were asked to stand on the treadmill while performing the SST.

This procedure was repeated a total of four times with each participant, one for each combination of initial stimulus and stop-signal modalities (AA, VA, AV, VV) at a single assigned level of physical exertion. A summary of the entire procedure is presented in Table 2. In general, the total duration of the experiment was approximately 1.25-1.5 hours.

Dependent Variables

Dependent variables collected during the experiment included go-signal response time (GSRT), stop-signal reaction time (SSRT), accuracy, and mental workload rating. GSRT was defined as the participant's time to respond to the initial stimulus in trials that did not contain a stop-signal. (Note that in each block, 25% of the trials contained stop signals while the rest presented the user with only the initial stimulus.) Stop-signal reaction time (SSRT) was calculated for each block of trials by subtracting the mean stop-signal delay time, defined as the elapsed time between the onset of the stimulus and the stop-signal (see Verbruggen et al., 2008 and Figure 2), from the mean GSRT for each participant under each stimulus-stop-signal modality combination. Accuracy was defined as the percentage of correct responses, including correct control selection in trials without a stop-signal and successful inhibition in stop-signal trials. Response accuracy in the go-signal trials and inhibition accuracy were analyzed separately. A unidimensional visual analog rating scale was used to assess perceived mental workload in the cognitive task. Participants were instructed to rate only their cognitive workload resulting from the combination of stimulus and stop-signal modalities to which they had just been exposed. Participants were told not to consider physical effort in their workload ratings. After each block of trials presenting a unique combination of stimuli modalities, the participant was asked to give a subjective rating by marking a point on a continuous (100 mm) scale with anchors of “low workload” and “high workload.” The distance from the left anchor to the marking was measured (with millimeter accuracy) and this distance was transformed to a value between zero and one.

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. Since some participants were military and others were not, military status was screened as a whole-plot factor and found to be non-significant ($p>0.05$) for all response variables (likely due to the comparable fitness level of the non-military participants). Thus, the demographic term was removed from all subsequent analyses. The split-plot factors included stimulus 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 found to be significant only for

GSRT. Thus, trial number was removed from all ANOVA models with the exception of the model for GSRT.

The experimental data were aggregated (i.e., means were calculated) to produce one observation for each participant under each combination of stimulus modality and stop-signal modality (i.e., four observations, in total, for each participant). Constant variance and residual normality were assessed using accepted statistical diagnostic procedures in order to ensure all ANOVA assumptions were met. If there was evidence of any assumption violation, either a log or arcsin transformation was applied to the raw responses, or the responses were ranked in order to conduct a nonparametric ANOVA. Overall accuracy, go-signal response accuracy, and cognitive workload ratings required transformations (as described below). Unless otherwise noted, all multiple comparison post-hoc tests were performed using Tukey's Honest Significant Difference (HSD) procedure.

A significance level of $\alpha = 0.05$ was used as a criterion for establishing statistical significance of all ANOVA and post-hoc test results. For some response measures, we have also reported marginally significant results, based on an $\alpha = 0.10$ criterion. For all statistical tests, we also report observed or post-hoc power ($1-\beta$) values. However, we note that prior statistical research has shown that such values actually share a 1:1 correspondence with the attained p-value for a test (Hoenig & Heisey, 2001). For small (and significant) p-values, the post-hoc power value appears great and for large p-values, even in the case that the null hypothesis is probably true, the post-hoc power is low (Hoenig & Heisey, 2001). All main effect and interaction plots in this section present untransformed means (regardless of whether the response was transformed for the ANOVA). The plots also include error bars representing one standard deviation from the mean, and display any significant post-hoc groupings at the base of bars, where levels that do not share the same letter are significantly different, according to Tukey's HSD statistical test.

Results

Overall Accuracy

Due to a lack of effectiveness of log or arcsin data transformations to resolve ANOVA assumption violations, a nonparametric ANOVA was performed on the ranked accuracy and revealed no significant main effects or interactions (stimulus modality $F(1,54) = 1.836$, $p = 0.181$, $1-\beta = 0.265$; stop signal modality $F(1,54) = 0.303$, $p = 0.584$, $1-\beta = 0.084$; stimulus modality x stop-signal modality $F(1,54) = 0.716$, $p = 0.401$; exertion level x stimulus modality $F(2,54) = 0.988$, $p = 0.379$; exertion level x stop-signal modality $F(2,54) = 0.729$, $p = 0.487$; 3-way interaction $F(2,54) = 0.081$, $p = 0.922$); however, there was a marginally significant effect of exertion level ($F(2,19) = 2.886$, $p = 0.080$, $1-\beta = 0.685$). Tukey's HSD post-hoc test revealed accuracy at the 0% VO_2max level to be significantly higher than the accuracy at the 70% VO_2max level. Neither of these levels was significantly different from the 50% VO_2max condition. As shown in Figure 3, overall accuracy decreased as exertion level increased, but accuracy was high across all three exertion levels.

Inhibition Accuracy

An ANOVA performed on inhibition accuracy revealed a significant effect of initial stimulus modality ($F(1,54) = 11.795$, $p = 0.001$, $1-\beta = 0.921$). All other main effects and interactions were non-significant at the $\alpha = 0.05$ significance level (exertion level F(2,19) = 0.675, p = 0.521, $1-\beta = 0.921$; stop signal modality F(1,54) = 0.082, p = 0.776, $1-\beta = 0.059$; stimulus modality x stop-signal modality F(1,54) = 1.311, p = 0.257; exertion level x stimulus modality F(1,54) = 0.118, p = 0.889; exertion level x stop-signal modality F(2,54) = 1.511, p = 0.091; 3-way interaction F(2,54) = 0.177, p = 0.838). Mean (SD) inhibition accuracy was 69.0% (13.8%) for auditory stimuli and 58.9% (15.4%) for visual stimuli; participants were more accurate inhibiting their responses when exposed to an auditory stimulus as compared to the visual left and right arrows.

Go-Signal Response Accuracy

A nonparametric ANOVA on the go-signal response accuracy revealed a significant interaction between exertion level and stimulus modality (F(2,54) = 4.556, p = 0.015). All main effects were non-significant (exertion level F(2,19) = 0.771, p = 0.476, $1-\beta = 0.712$; stimulus modality F(1,54) = 2.836, p = 0.098, $1-\beta = 0.380$; stimulus modality x stop-signal modality F(1,54) = 0.454, p = 0.503; exertion level x stop-signal modality F(2,54) = 2.563, p = 0.086; 3-way interaction F(2,54) = 0.704, p = 0.499). Here, it is important to note that, in all stop-signal tests as part of a trial block, the stop-signal stimulus always followed the initial stimulus. Although trial blocks were defined in terms of the modality of the initial and stop-signal stimuli, the timing of these signals was not represented in the experimental design or statistical analysis models. As a result of the actual timing of the stimuli (one relative to another), any direct influence of an inhibitory stimulus on go-signal performance was not possible. Consequently, the stop-signal modality and any higher order interaction involving this term were not included in the ANOVAs on GSRA. Regarding the significant interaction of exertion level and go-signal modality, there were no significant differences among exertion levels when the visual arrows were presented; however, there were differences among the three exertion levels when the words “left” and “right” were presented by digitized speech. These results are summarized in Figure 4.

Stop-Signal Reaction Time

An ANOVA on the SSRT revealed a significant main effect of the initial stimulus modality ($F(1,54) = 14.066$, $p<0.001$, $1-\beta = 0.958$). No other main effects or interactions were significant (exertion level $F(2,19) = 0.742$, $p = 0.490$, $1-\beta = 0.529$; stop signal modality $F(1,54) = 0.991$, $p = 0.324$, $1-\beta = 0.165$; stimulus modality x stop-signal modality $F(1,54) = 0.803$, $p = 0.374$; exertion level x stimulus modality $F(2,54) = 0.713$, $p = 0.494$; exertion level x stop-signal modality $F(2,54) = 1.732$, $p = 0.187$; 3-way interaction $F(2,54) = 1.204$, $p = 0.308$). Mean (SD) SSRT was 0.466 sec (0.048 sec) for when the stimulus was presented auditorally and 0.408 (0.058 sec) when visual arrows were presented.

Go-Signal Response Time

An ANOVA on the GSRT revealed significant main effects of trial number ($F(1,53) = 8.152$, $p = 0.006$) and initial stimulus modality ($F(1,53) = 68.364$, $p<0.001$, $1-\beta = 1.000$). (As mentioned in the go-signal response accuracy analysis, there is no causal relationship between the stop-signal modality and the GSRT; therefore, the stop-signal modality and any higher order interaction involving this term were not included in the ANOVA on GSRT.) There was no significant effect of exertion level ($F(2,19) = 0.141$, $p = 0.870$, $1-\beta = 0.110$), or the interaction between exertion level and stimulus modality ($F(2,54) = 0.153$, $p = 0.858$). With respect to the stimulus modality main effect, a mean GSRT for auditory stimuli of 0.86 sec was observed along with a mean GSRT for visual stimuli of 0.68 sec.

Cognitive Workload Rating

An ANOVA on the log-transformation of the cognitive workload ratings revealed no significant main effects or interactions at the $\alpha = 0.05$ significance level (exertion level $F(2,19) = 1.264$, $p = 0.305$, $1-\beta = 0.930$; stop-signal modality $F(1,51) = 1-\beta = 0.194$; stimulus modality x stop-signal modality $F(1,51) = 0.335$, $p = 0.565$; exertion level x stimulus modality $F(2,51) = 1.854$, $p = 0.167$; exertion level x stop-signal modality $F(2,51) = 0.773$, $p = 0.467$; 3-way interaction $F(2,51) = 0.251$, $p = 0.778$). However, there was a marginally significant effect of stimulus modality ($F(1,51) = 2.915$, $p = 0.094$, $1-\beta = 0.388$) at the $\alpha = 0.10$ significance level. The mean (SD) workload rating, on a scale from 0 to 1, was 0.25 (0.22) in conditions presenting auditory stimuli and 0.27 (0.20) in conditions presenting visual arrows as stimuli.

Discussion

Hypothesis 1 posited that presentation of visual stimuli would result in lower response accuracy. Results supported the hypothesis, particularly for inhibition accuracy. In general, task accuracy was very high and similar to accuracies reported by Boehler et al. (2012), Padilla et al. (2013), and Gan et al. (2014), using the standard SST paradigm with visual stimuli and auditory stop-signals. Results for inhibition accuracy and go-signal accuracy showed auditory initial stimuli to produce higher accuracy, which may be due to the fact that auditory cues are more attention demanding (Rauterberg, 1998) and may require more time to process, as compared to visual cues (Cowan, 1988). Therefore, it is possible that the time to process the auditory stimuli was longer than the delay time between the stimulus and the stop-signal, making it easier to inhibit responses and to respond when inhibition was not necessary.

The second hypothesis stated that presentation of visual stimuli would result in lower GSRT. In support of the hypothesis, results revealed participants to react more quickly when exposed to visual stimuli as compared to auditory. This effect is in-line with theory that auditory cues may require greater internal processing time than visual cues (Cowan, 1988). However, the results of the current experiment are contradictory to previous research, which found that choice RT is generally shorter for auditory stimuli than for visual stimuli (Niemi, 1978; Green and von Gierke, 1983). Green and von Gierke (1983) attributed their results to differences in "detectability"; that is, it was more difficult for their participants to detect the visual stimuli than the auditory stimuli. In the present experiment, it is possible that it was easier to detect the visual arrow stimuli, which were displayed directly in the participants' forward field of view, potentially accounting for the GSRT results. Furthermore, Yagi et al. (1999) examined differences in RTs to visual and auditory stimuli in oddball tasks under aerobic exercise. Their results indicated that RT was faster for the visual than for the auditory task across three conditions (baseline, exercise, and recovery). Considering the various application environments identified in the motivation, the results suggest that reaction-time-critical information should be visually presented to soldiers, firefighters, police, etc. whenever possible. However, the treadmill running task used in the current experiment may not account for normal cognitive load associated with running across rough terrain in real environments. Furthermore, real-world running requires self-pacing, another cognitive element that is not required in treadmill running. Previous research in this area has demonstrated increased cognitive loads associated with running compared to cycling (Lambourne and Tomporowski, 2010) and with word recall during a traverse-climbing task compared to a non-climbing condition (Green and Helton, 2011; Green et al., 2013; Darling and Helton, 2014). It is likely that these findings on increased cognitive load under realistic task conditions extend to over-ground running on changing terrain, as compared with treadmill running. Therefore, it is possible that our assessment of the influence of physical workload on cognitive task performance in the present study is relatively conservative compared to any effects that might be observed in a comparable real-world task scenario involving cognitive performance while running over-ground.

The third hypothesis posited that presentation of visual signals would result in lower SSRT. Results supported the hypothesis and revealed that participants required more time to inhibit their response when stimuli were presented aurally. The lack of a significant main effect of stop-signal modality, or interactions involving stop-signal modality, suggest the manipulation had no effect on the time it took to inhibit a response. The lack of an interaction between the stimulus modality and the stop-signal modality also suggests participants had no problems switching between modalities (e.g., inhibiting response to a visual stop-signal after hearing an initial auditory stimulus) compared to trials presenting both signals with the same modality. This finding is contradictory to some results in the existing literature (e.g., Spence and Driver, 1997; Lukas et al., 2010). It is possible that exercise-induced arousal resulting from the physical loading task (e.g., increased heart rate, increased blood adrenaline concentration, etc.) promoted participant ability to switch between modalities in order to correctly inhibit their responses. Since SSRT was calculated by subtracting the mean delay time from the mean GSRT, a longer SSRT when exposed to auditory go-signals may also be due to a longer time to process auditory signals (Cowan, 1988).

The fourth hypothesis stated that the presentation of visual signals would result in lower perceptions of cognitive workload. Results indicated perceived workload to be related to the initial stimulus modality but not influenced by the combination of initial and stop-signal modalities. Under the conditions where a visual stimulus was presented, participants tended to perceive higher mental workload. Despite research suggesting that auditory stimuli are more attention-demanding (Rauterberg, 1998), it is possible that the concurrent jogging task made it difficult to focus visual attention on the SST, since participants were constantly moving up and down due to their running motion. Opposite to this, direction of attention was not required for the auditory signals. Since the significance level of the stimulus modality manipulation ($p = 0.0904$) was marginal, it is possible that the result might be due to random variation in responses.

Hypothesis 5 posited that moderate physical exertion (compared to high and low levels) would result in higher response accuracy. This hypothesis was rejected for overall accuracy and inhibition accuracy. Results revealed overall accuracy to be relatively high across all conditions and the physical exertion level did not significantly affect overall accuracy at the $\alpha = 0.05$ significance level. Overall accuracy did decrease as exertion level increased but this trend was only marginally significant ($p<0.10$). It is possible that since all participants were in good shape, the 70% VO_2max exertion level was not highly demanding. Hypothesis 5 was also rejected for go-signal accuracy when the stimulus modality was visual. However, results revealed a significant effect of exertion level on accuracy when auditory stimuli were presented such that participants were significantly more accurate for auditory stimulus responses while they were standing in comparison to running at the 70% exertion level. This observation goes against the “Inverted U” hypothesis (e.g., Reilly and Smith, 1984), but supports other research suggesting that increasing the attentional and metabolic resources required by the physical task decreases the availability of those resources to the cognitive task, resulting in poorer performance (Audiffren, 2009). Although the auditory signals were loud enough to hear clearly under all conditions, it is possible that when running at high speed, the noise from the treadmill and the sound of feet repeatedly hitting the treadmill might have distracted participants. This situation could have degraded response accuracy, as compared to the 0% VO_2max condition.

Hypothesis 6 posited that moderate physical exertion (compared to high and low physical exertion levels) would result in shorter GSRT. Again, results indicated that there was no significant effect of physical exertion level on GSRT. The response time to a signal that did not require inhibition (i.e., a go-signal) was not affected by physical exertion level. As with response accuracy, this result is likely attributable to the high fitness of the participants. The result is 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. Responses to the go-signal are a choice response time task, which requires processing of the signal and decision on a response. Therefore, the task was likely complex enough to not be more affected by the physical loading condition. Furthermore, Chang et al. (2012) concluded that the disparate findings on the effect of physical exertion level on reaction time suggest the response is not affected by exertion, or is not particularly reliable or sensitive as a measure of cognitive performance. This contention is reflected in our GSRT results.

Hypothesis 7 stated that moderate physical exertion (compared to high and low) would result in shorter SSRT. Results revealed no effect of physical exertion on SSRT. This finding may also be attributed to the high fitness level of participants. Related to this, it is possible that increased heart rate, sweating, and increased blood adrenaline concentration did not differ enough among the physical exertion levels for our participants in order to cause a difference in performance in the SST (Brisswalter et al. 2002). Another potential explanation, similar to the findings regarding GSRT, is that response inhibition, which is a top-down executive process, is not affected by exertion level since it is not a simple, bottom-up response (Lambourne and Tomporowski, 2010). Chang et al. (2012) stated that the results of each experiment depend on particular cognitive tasks and specific exercise types and intensities. Therefore, the present results may have limited generalizability to other combinations of physical and cognitive tasks (e.g., performing the Stroop test while cycling).

Our findings were different from some prior studies indicating that moderate physical exertion intensity improves cognitive performance (e.g., Reilly and Smith, 1986; Brisswalter et al., 2002). However, the present findings do support other studies that found no significant effect of physical exertion level on cognitive performance. For example, Sjoberg (1980) observed cycling at 0%, 25%, 50%, 75% VO_2max to have no effect on cognitive task performance. However, their study was different from the current research as the cognitive task was a short-term memory test. In another study, Fleury et al. (1981) evaluated effects of two different treadmill protocols on young men's visual perception. One protocol involved running five 1.5-min bouts at a speed eliciting exertion comparable to VO_2max at 5-min intervals; the other protocol was to run continuously to voluntary exhaustion with increasing speed and grade of a treadmill. They found that neither protocol influenced participant performance during a letter-detection task. Finally, the meta-analysis by Chang et al. (2012) and a review by Lambourne and Tomporowski (2010) suggest that cognitive performance benefits are evident when the physical exertion lasts more than 20 minutes. This may further explain the lack of a significant effect of exertion level in the present study.

Hypothesis 8 posited that moderate physical exertion (compared to high and low levels) would result in lower perceptions of cognitive workload due to potential competition for resources between the physical and cognitive tasks (Chang et al., 2012). Again, results did not reveal a significant effect of physical exertion level on cognitive workload. As previously mentioned, participants were likely fit enough that the physical task required limited cognitive resources, allowing them to focus on the SST.

According to Hypothesis 9, it was expected that our hypotheses regarding information presentation modality (H1-H4) would be exaggerated under moderate physical loading compared to the high and low levels of physical loading due to the increased physiological arousal associated with moderate exertion levels. Although there were a couple instances where there was a significant interaction between the exertion level and the modality of information presentation, results generally refuted the hypothesis. The significant interaction between exertion level and stimulus modality on mean go-signal accuracy suggests that auditory signals affect cognitive task performance differently than visual signals under increased physical loading. As mentioned previously, this may be related to the “detectability” of the stimuli suggested by Green and von Gierke (1983); the visual signals, which were presented directly in the runners' line of sight, were much more detectable than the auditory signals, which needed to be processed above the sound of the treadmill and participant feet hitting the treadmill deck. In general, the results of the experiment suggest that there was very little interaction between the modality of information presentation and the physical exertion on performance in a concurrent cognitive inhibition task.

Conclusions

The objective of this research was to investigate the effect of physical workload and different modalities of information presentation on concurrent cognitive task performance. Very little research has examined the interaction between physical exertion level and modality of cognitive task information presentation on task performance. Based on the results, cognitive task accuracy was high regardless of exertion level and modality of information presentation. In addition, it was found that highly fit individuals were able to inhibit cognitive task responses quickly and accurately at physical exertion levels up to 70% VO_2max. There was no difference between modalities of the stop-signal while performing a physical task. However, our results also revealed that high-fitness individuals are able to inhibit responses more quickly when the stimulus is presented visually vs. auditorally.

One application for this research is the determination of optimal information presentation approaches for occupations requiring simultaneous physical and cognitive task performance, particularly from a display design perspective. Based on our findings, presenting visual information will result in faster inhibition responses compared to presentation of auditory stimuli. This information could be helpful in designing wearable technology or other portable information displays, such that time-critical alerts may be more effective if they're presented visually rather than auditorally. Although the participants in this study were primarily selected from a military population, the results of the study can likely extend to other occupations that demand cognitive processes during concurrent physical loading, such as police work or firefighting.

Limitations

One limitation of the present research was use of a maximum physical exertion level of 70% of VO_2 max. This level was chosen to assess the effect of high physical exertion on cognitive performance (beyond the 40-60% of VO_2max range that Reilly and Smith (1986) showed to improve cognitive performance) without risking the safety of the participants with a maximum level. It is possible that the 70% of VO_2max level was not demanding enough for the high-fit participants recruited for our experiment. We used an estimate of VO_2max for high fit males, based on the results of Swain et al. (1994), in order to determine the treadmill test speeds representing the various levels of physical workload for participants. Of course, individual differences exist in aerobic capacity and, therefore, 4.9 mph might not have corresponded to exactly 50% VO_2max for all participants. Furthermore, it is possible that self-paced over-ground running on changing terrain likely imposes a greater cognitive load than treadmill running, potentially limiting the generalizability of the results to an equivalent real-world task. Another limitation of this study was that some of the participants were non-ROTC students. Although the fitness criteria used for selecting non-ROTC students were the same as military physical fitness requirements, further consistency in the participant sample might increase the reliability of results. Finally, it is possible that the noise from the treadmill and the sound generated by participant feet hitting the treadmill surface influenced performance in the stop-signal task, particularly in conditions that presented auditory stimuli. However, given the approximate 10-dB sound-level difference between the treadmill and the auditory cues, any influence was likely negligible.

Future Work

Future work could investigate performance tradeoffs under more demanding physical and cognitive task conditions. In addition to the high fit male population studied here, a high fit female population should also be examined. Regarding the limitation of using the same treadmill speed for all participants, future work should assess VO_2max for each participant using a previously validated method, such as the Siconolfi step test (Siconolfi et al., 1985) or the heart rate ratio method (Uth et al., 2005). This estimation can then be used identify personalized treadmill speeds representing each physical workload level. Other future work could include examination of cognitive task information presentation modalities other than visual and audio, such as haptic encoding. Haptic feedback has been studied in driving simulation research in order to provide alerts for directions of hazards in potential collision situations (e.g. Fitch et al., 2007). It may also be also beneficial to provide haptic signals in response inhibition tasks and to compare effectiveness with visual and audio signaling during simultaneous physical task performance. Finally, the SST used in current research was a test of executive function. In order to better understand the effect of physical exertion level on cognitive performance with multiple modalities of information presentation, various types of cognitive tests (i.e., decision making, and memory tasks) could be used in future research.

Conflict of Interest

The authors declare no conflict of interest.

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Table 1: Stop-signal Task Modality Descriptions

Signal and Modality		**Description**
Stimulus		
	Visual (V)	White right or left arrow in the middle of the screen
	Auditory (A)	Digitized voice saying “left” or “right”
Stop-signal		
	Visual (V)	Red text displaying “STOP” in the middle of an arrow stimulus
	Auditory (A)	Auditory beep (750 Hz, 75 ms)

Table 2: Summary of the Procedure for Each Participant

Number	Event	Time (min)
1	Initial Paperwork, SST Training, etc.	15
2	APFT (non-military participants only, including rest period)	15
3	Training and Jog Number 1	9
4	Rest Period 1	5.5-6.5
5	Training and Jog Number 2	9
6	Rest Period 2	5.5-6.5
7	Training and Jog Number 3	9
8	Rest Period 3	5.5-6.5
9	Training and Jog Number 4	9
10	Concluding Remarks and Paperwork	5
	Total Time	75.5-90.5

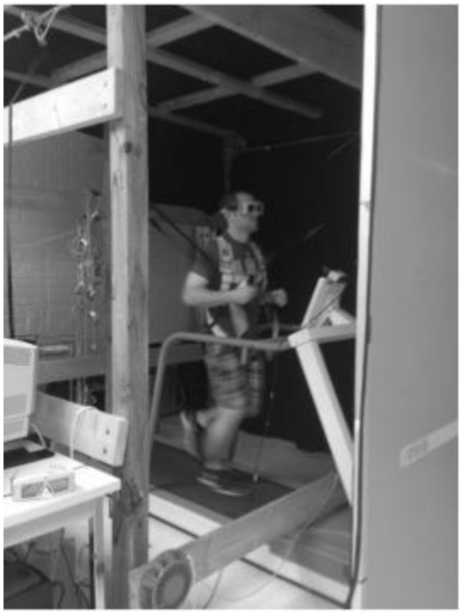

Figure 1: Setup for the Virtual Reality Locomotion Interface, Including Treadmill and Projection Screen

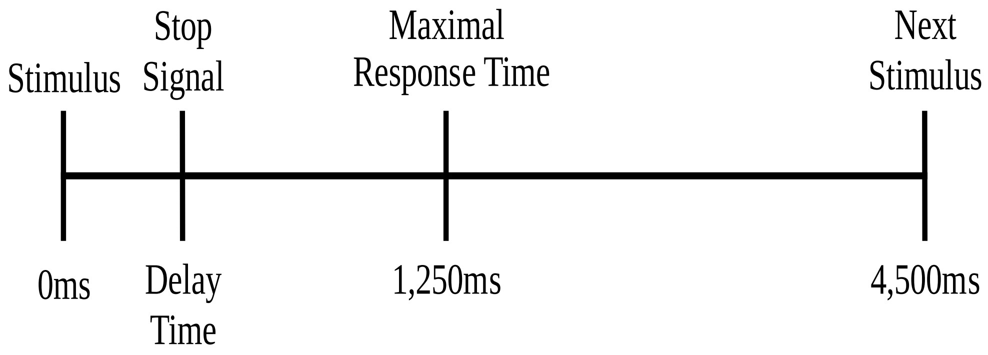

Figure 2: Timeline of Stop-signal Task Events

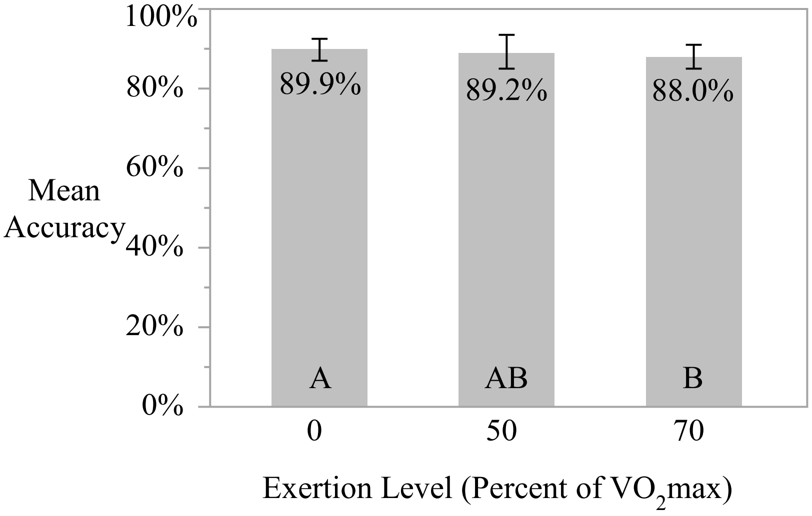

Figure 3: Marginal Effect of Exertion Level (p = 0.080) on Overall Accuracy

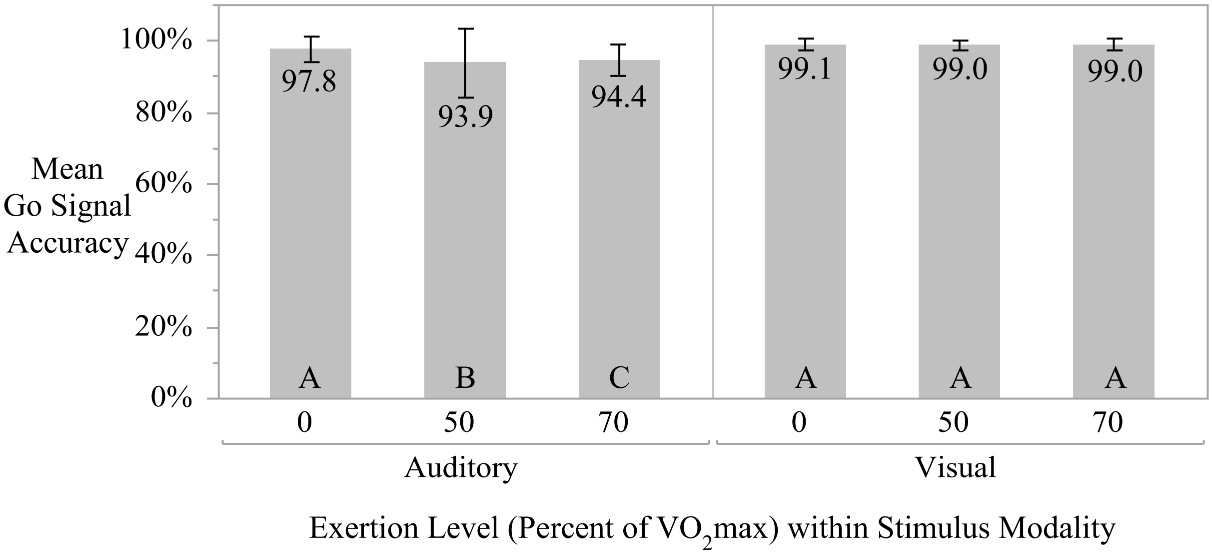

Figure 4: Effect of Exertion Level and Stimulus Modality Interaction on Go-Signal Accuracy