Effects of Mental Fatigue on the Development of Physical Fatigue: A Neuroergonomic Approach

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Objective: The present study used a neuroergonomic approach to examine the interaction of mental and physical fatigue by assessing prefrontal cortex activation during submaximal fatiguing handgrip exercises.

Background: Mental fatigue is known to influence muscle function and motor performance, but its contribution to the development of voluntary physical fatigue is not well understood.

Method: A total of 12 participants performed separate physical (control) and physical and mental fatigue (concurrent) conditions at 30% of their maximal handgrip strength until exhaustion. Functional near infrared spectroscopy was employed to measure prefrontal cortex activation, whereas electromyography and joint steadiness were used simultaneously to quantify muscular effort.

Results: Compared to the control condition, blood oxygenation in the bilateral prefrontal cortex was significantly lower during submaximal fatiguing contractions associated with mental fatigue at exhaustion, despite comparable muscular responses.

Conclusion: The findings suggest that interference in the prefrontal cortex may influence motor output during tasks that require both physical and cognitive processing.

Application: A neuroergonomic approach involving simultaneous monitoring of brain and body functions can provide critical information on fatigue development that may be overlooked during traditional fatigue assessments.

Keywords: cognitive demand, motor performance, endurance, near infrared spectroscopy, cerebral oxygenation, prefrontal cortex

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INTRODUCTION

Muscle fatigue is a complex, multifaceted phenomenon and is most commonly defined as the inability to maintain a required force level after prolonged use of the muscle (Latash, Danion, & Bonnard, 2003). The contributors to *voluntary* fatigue, henceforth referred to simply as fatigue, may be either peripheral or central, or both, but investigators have typically focused on only one source alone. Isolating the muscle or the brain in separate investigations can offer only a partial understanding of the mechanisms underlying the development of fatigue. Traditional ergonomic evaluations to quantify muscle fatigue are limited to peripheral biomechanical, muscular, and physiological responses, that is, are focused on the body. What about the brain? Neuroimaging techniques, such as electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and positron emission tomography (PET), have demonstrated direct linear relationships between muscle activity and neural activity in several motor function-related cortical regions, indicating increased neural command signals to descending motor neurons (Dai, Liu, Sahgal, Brown, & Yue, 2001; Siemionow, Yue, Ranganathan, Liu, & Sahgal, 2000). In addition, EEG techniques have revealed that fatigue-related changes in brain function include distinct shifting of cortical activation centers to maximize central command to muscles during a fatiguing task so that physical performance can be maintained (Liu et al., 2007). Thus, examining the role of brain functioning during fatigue development is critical to extend our knowledge on the etiology and potential mechanisms of fatigue. Such a view is consistent with neuroergonomics, which has generally been used in the evaluation of cognitive work (Parasuraman, 2011; Parasuraman & Rizzo, 2008), but which can also be applied to the assessment of and interaction between cognitive and physical work

(Karwowski, Siemionow, & Gielo-Perczak, 2003; Parasuraman & Mehta, in press).

Of the neuroimaging techniques that are available to investigate motor function in the field of neuroergonomics, functional near infrared spectroscopy (fNIRS) is an emerging tool for noninvasively monitoring the hemodynamic response to brain activation. fNIRS offers good temporal resolution and permits evaluation of movement-based motor activities with relative ease, and is thus an attractive alternative to traditional neuroimaging techniques like EEG and fMRI. fNIRS provides measures of cerebral oxy- and deoxyhemoglobin levels that reflect changes in neuronal input and/or processing during cognitive work (Ayaz et al., 2012; Carter, Russell, & Helton, 2013; McKendrick, Ayaz, Olmstead, & Parasuraman, 2013; Schreppel et al., 2008). In investigating muscle fatigue development, there is consensus that fatigue is associated with a critical reduction in prefrontal oxygenation, accompanied by muscular impairment, at exhaustion (Bhambhani, Malik, & Mookerjee, 2007; Nybo & Rasmussen, 2007; Thomas & Stephane, 2008). These findings suggest that changes in prefrontal cortex (PFC) activation may contribute to the reduction in motor output at the cessation of exercise.

With the growth of automation in work settings, it has become increasingly important to integrate human physical, cognitive, and affective capabilities and limitations in ergonomic design and evaluation processes. Along with physical risk factors, such as force, prolonged duration, and repetition, cognitive stressors and mental fatigue have also been shown to accelerate muscle fatigue development and hinder recovery (Mehta & Agnew, 2012). Mental fatigue-related changes in muscle capacity, measured using electromyography (EMG), have been attributed to (a) increased loading of the musculoskeletal system due to altered motor coordination that results in higher muscle co-contraction (Mehta & Agnew, 2011; Mehta, Nussbaum, & Agnew, 2012; van Loon, Masters, Ring, & McIntyre, 2001) or (b) increased neuromotor noise that can disturb motor control or joint steadiness (Gemmert & Galen, 1997). A few studies also emphasize the contributions of the PFC as an interference site for physical and mental fatigue interaction (Marcora, Staiano, & Manning, 2009; Mehta & Agnew, 2012). fMRI and PET studies have revealed that the dorsolateral prefrontal region is activated during separate cognitive processing of working memory tasks and isometric motor contractions, respectively (Dettmers, Lemon, Stephen, Fink, & Frackowiak, 1996; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000). Thus, it is possible that performance during concurrent physical and cognitive tasks that require neural activation of the PFC may be compromised. In the present study we examined this neural interference theory using simultaneous monitoring of brain and muscle function.

Existing concurrent assessment of physical and mental fatigue is limited to evaluating cardiovascular, muscular, and biomechanical changes (Lundberg et al., 2002; Marras, Davis, Heaney, Maronitis, & Allread, 2000; Mehta & Agnew, 2013). Along with the commonly used indicators, employing neuroergonomic techniques such as EEG and fNIRS to evaluate cortical function can provide important information concerning the changes in the motor cortex under concurrent physical and mental work. The purpose of this study was to examine the interaction of physical and mental fatigue on PFC activation during submaximal fatiguing handgrip exercises using fNIRS. A secondary purpose was to compare the changes in neural patterns with traditional indicators of muscle fatigue, such as muscle activity and joint steadiness.

METHOD

Participants

A total of 12 young adults, balanced by gender, participated in this study, with mean (*SD*) age, height, and body mass of 21.4 (1.1) years, 172.9 (7.5) cm, and 74.2 (15.5) kg, respectively. All participants were right-handed, based on self-reports, and admitted to be in good health, with no upper-extremity injuries or physical disorders currently or within the prior year. Written informed consent, using procedures approved by the institutional review board, was obtained from all participants.

Experimental Protocol

Before the start of the study, participants were familiarized with the protocol and were

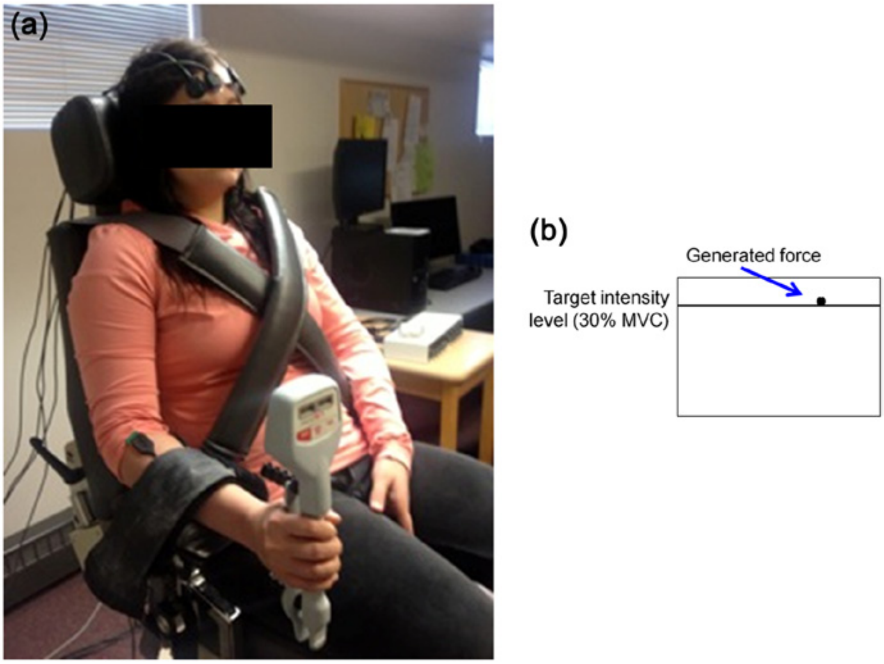

Figure 1. (a) Posture adopted during submaximal handgrip exercises and (b) real-time feedback provided to the participants.

instructed to perform warm-up exercises by intermittently gripping a stress ball for 2 min. Upon adequate rest, fNIRS probes (NIRO 200 NX, Hamamatsu Photonics, Japan) and EMG electrodes (BIOPAC Systems, Inc., Santa Barbara, CA, USA) were placed on the forehead and on lower arm muscles, respectively. A series of three maximal handgrip strengths were collected using a handgrip dynamometer (microFET 4, Hoggan Health Industries Inc., West Jordan, UT, USA), with sufficient rest periods of ~2 min between each collection, in a seated posture illustrated in Figure 1a. Additional rest was provided to participants based on the feedback of their perceived discomfort. The experimental task required participants to perform sustained handgrip endurance exercises at 30% maximal handgrip strength until exhaustion, in the absence and presence of a mental stressor. A serial-7 subtraction arithmetic task was employed to induce mental fatigue during the mental stressor protocol. Participants were provided with a three-digit number and were asked to verbally count backward by seven as accurately and quickly as they could (e.g., 143, 136, 129, etc.). At any time that the participants stated an incorrect response (i.e., an error), the correct response was provided and they used that number to continue counting backward by seven. This mental arithmetic task is a commonly used laboratory stressor targeting working memory capabilities, and has been shown to significantly increase vasodilator response (Carter, Kupiers, & Ray, 2005). During both endurance exercises, the order of which was counter-balanced, participants were instructed to maintain the target intensity level for as long as they could and precisely track their generated force against the target as closely as possible based on real-time visual feedback on a computer screen at eye height (Figure 1b). Endurance time was defined as the time at which the participant dropped more than 5% below the target without reattaining it. To avoid any bias, instructions were kept consistent among all participants; they were encouraged to perform their best in both the physical and mental arithmetic tasks. A minimum of 15 min of rest was provided after each endurance task. Participants were given more rest if their perceived discomfort was greater than 3 (from a scale of 0 = *nothing at all* to 10 = *extremely strong discomfort*) at the end of the 15-min recovery. To compare changes in cognitive performance in the concurrent fatigue condition, participants performed a reference mental arithmetic task (in the absence of any physical activity) for the longer of the two endurance times reported in the previous tasks.

Cerebral Oxygenation

Near-infrared spectroscopy probes (NIRO 200 NX, Hamamatsu Photonics, Japan) were placed bilaterally on the participant's forehead to measure cerebral oxygenation from the PFC. Based on the international EEG 10-20 system, the NIRS probes were positioned between Fp1 and F3 at the PFC. A headband was used to securely support the probe against the forehead, to minimize any light interference. fNIRS data were collected at 5 Hz at near-infrared light at wavelengths of 735, 810, and 850 nm, and changes in oxygenated hemoglobin (Oxy-Hb) and total hemoglobin index (THI) from initial values were recorded to test the differences between the fatiguing conditions. To obtain the initial values, participants were instructed to close their eyes and relax for 2 min. Based on the manufacturer's guidelines, the NIRS system was zero-set at the end of the first minute and all future data were presented relative to the zero-set values. Oxy-Hb and THI data were averaged across 10-s windows centered at 0%, 25%, 50%, and 100% endurance time for each participant, indicated henceforth as initial, 2nd, 3rd, 4th, and exhaustion, respectively.

Muscular Responses

Maximal handgrip strength obtained at the start of the session was compared to that at exhaustion, collected immediately following each fatiguing condition. Decrease in maximal strength is considered a "gold standard" measure of fatigue (Vøllestad, 1997). Endurance time was determined as the time to exhaustion, defined as the holding time until participants could not longer maintain the target force levels. Joint steadiness was measured as coefficient of variation (i.e., standard deviation/mean force × 100) during the fatiguing tasks through force output from the grip dynamometer. Handgrip forces were recorded continuously in each condition at 100 Hz, and force data were low-pass filtered at 15 Hz, and the middle 10-s of data across five time epochs (initial, 2nd, 3rd, 4th, and exhaustion) of each fatiguing exercise, similar to that employed for fNIRS data, were used for analysis.

For EMG data collection, muscle sites on each participant were shaved and cleansed with alcohol to reduce skin resistance, and EMG electrodes (BIOPAC Systems, Inc., Santa Barbara, CA, USA) were placed on the belly of the extensor carpi radialis (ECR) and the flexor carpi radialis (FCR), along the length of the muscle fiber. After 20 min of stabilization, a quiet EMG trial was collected to remove signal bias. All raw EMG signals were band-passed filtered (20–450 Hz) in hardware, sampled at 1000 Hz, full-wave rectified, then corrected for resting levels, low-pass filtered (dual pass, 4th order Butterworth filter with effective cutoff frequency of 3 Hz), and normalized to maximal values (obtained from maximal handgrip exertions). Root mean squared (EMG RMS) values for each muscle were quantified by averaging across the 10-s windows, across the five stages of each fatiguing exercise. To obtain the power spectrum, median power frequency (MdPF) was calculated within 10-s windows across the five time epochs of the raw EMG signal in each condition using a Hamming window and fast-Fourier transform.

Performance and Self-Reports

Cognitive performance was assessed as the number of correct responses obtained when performing arithmetic tests during the endurance exercise and the reference mental fatigue task. Ratings of perceived exertion (RPEs) were obtained from participants after each fatiguing condition using the Borg CR10 scale; the anchors were set at 0 (*nothing at all*) and 10 (*extremely strong, almost max*; Borg, 1990). In addition, subjective workload was assessed using the paper/pencil version of the NASA Task Load Index (NASA-TLX), to assess workload across six dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration (Hart &

Staveland, 1988). Participants were asked to rate the level of each subscale in increments of high, medium, and low estimates in 21 gradations.

Statistical Analyses

A hemisphere (right vs. left) × task (physical fatigue vs. concurrent physical and mental fatigue) × time (5 time epochs) × gender split-plot analysis of variance (ANOVA) was performed to test differences in cerebral oxygenation levels. Separate split-plot ANOVAs were employed to test the effects of task (physical fatigue vs. concurrent physical and mental fatigue), time (5 time epochs), and gender on EMG RMS, EMG MdPF, and joint steadiness data. Separate two-way split-plot ANOVAs were performed to examine the effects of task (physical fatigue vs. concurrent physical and mental fatigue) and gender on endurance time, strength loss, and RPE. NASA TLX responses were evaluated using a three-way split-plot ANOVA with task (physical fatigue vs. concurrent physical and mental fatigue vs. reference mental fatigue), subscales (6 subscales), and gender as the test variables. A task (concurrent physical and mental fatigue vs. reference mental fatigue) × gender split-plot ANOVA was performed to test changes in mental task performance, and finally, a three-way split-plot ANOVA was employed to test the effects of hemisphere, time, and gender on cerebral oxygenation during the reference mental fatigue condition over time. Bonferroni corrections were used for post hoc comparisons where significant interactions were found. Statistical significance was determined when $p < .05$ and Huynh-Feldt corrections were applied if the assumption of sphericity was violated. All statistical analyses were conducted using SPSS 21 (IBM SPSS Statistics). All data are expressed as mean (*SD*).

RESULTS

Cerebral Oxygenation

THIs, across the right and left PFC, were not significantly affected by gender, time, task, or any two- or three-way interactions. Since THI levels remained stable over time and across both tasks (Figure 2a), further analyses of cerebral oxygenation were performed using Oxy-Hb levels, as Oxy-Hb is the most sensitive indicator of regional cerebral blood flow (Hoshi, Kobayashi, & Tamura, 2001). Oxy-Hb increased significantly over time, $F(4, 40) = 25.73$, $p < .0001$, $\eta_p^2 = .72$. A significant hemisphere × time interaction was found, $F(4, 40) = 8.76$, $p = .004$, $\eta_p^2 = .47$; pairwise comparisons revealed that the Oxy-Hb levels were higher in the right hemisphere than the left at exhaustion (Figure 2b). A significant task × time interaction was also found, $F(3.13, 40) = 3.43$; $p_{HF} = .027$, $\eta_p^2 = .255$. Post hoc comparisons between tasks at each time epoch using the Bonferroni correction revealed that Oxy-Hb levels during the concurrent physical and mental fatigue condition were significantly higher than the physical fatigue condition in the 1st and the 2nd time epochs. However, oxygenation levels at exhaustion (i.e., 5th time epoch) were significantly lower in the concurrent fatigue conditions when compared to the physical fatigue condition (Figure 2c). No significant differences in oxygenation levels between the two conditions were observed in the 3rd and 4th time epochs. No significant main effect of gender, or its interaction with other variables, was observed. The three-way split-plot ANOVA to test the effects of hemisphere, time, and gender on cerebral oxygenation during the reference mental fatigue condition revealed a significant main effect of time, $F(4, 40) = 4.84$, $p = .003$, $\eta_p^2 = .326$. Pairwise comparisons indicated that the cerebral oxygenation levels at the 1st time epoch were significantly lower than at 3rd or 4th time epochs. Both hemisphere and gender did not influence oxygenation levels during the reference mental fatigue condition (Figure 2d).

Muscular Responses

Endurance times in the physical fatigue and concurrent fatigue conditions were 166.75 (68.57) s and 165.08 (78.13) s, respectively, and did not differ significantly from each other. On average, participants' postendurance handgrip strength was ~71% (8) of their initial strength, and there was no main effect of task on strength loss. Higher endurance times, $F(1, 10) = 5.221$, $p = .045$, $\eta_p^2 = .343$, and greater strength decline, $F(1, 10) = 4.317$, $p = .064$, $\eta_p^2 = .302$, were observed for males ($M = 200.58$ s,

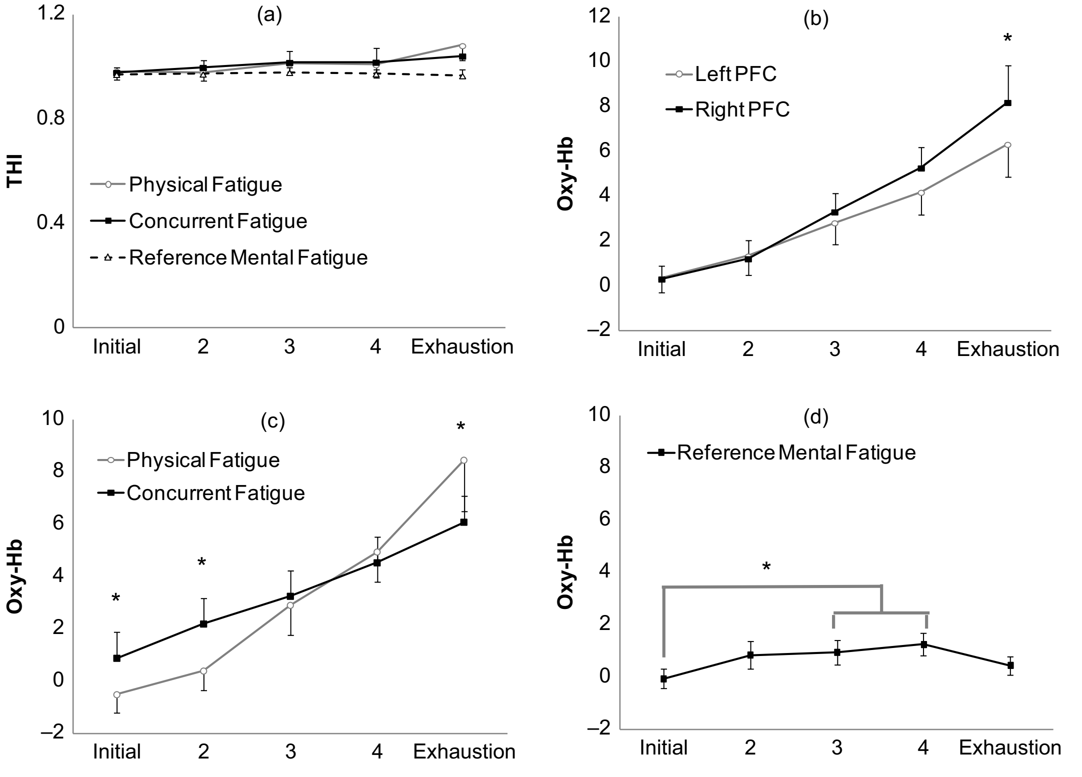

Figure 2. Changes in (a) total hemoglobin indices (pooled across hemispheres), (b) oxygenated hemoglobin across the right and left PFC (pooled across tasks), (c) oxygenated hemoglobin during the physical and concurrent fatigue conditions (pooled across hemispheres), and (d) oxygenated hemoglobin during the reference mental fatigue condition (pooled across hemispheres), across the five time epochs. Error bars represent standard error. The asterisk indicates a significant ($p < .05$) difference between the conditions within each time epoch in (b) and (c), and a significant difference between the time epochs in (d).

SD = 66.36 and *M* = 68.13%, *SD* = 7.09) than females (*M* = 132.42 s, *SD* = 49.79 and *M* = 73.82%, *SD* = 7.16).

Changes in joint steadiness, measured using force fluctuations, across the five stages are shown in Figure 3a. Higher fluctuations were observed at the 5th time epoch (i.e., at exhaustion) compared to the 2nd, 3rd, and 4th time epochs across both conditions, $F(4, 40) = 6.96$, $p < .0001$, $\eta_p^2 = .41$. Although greater fluctuations were observed in the concurrent fatigue condition compared to the physical fatigue condition at exhaustion (~50% vs. ~34% increase from initial values; Figure 3a), the effects of task or task × time interaction were not significant. EMG RMS values of the FCR and ECR muscles increased significantly over time across both conditions, FCR: $F(4, 40) = 24.86$, $p < .0001$, $\eta_p^2 = .713$; ECR: $F(4, 10) = 11.37$, $p < .0001$, $\eta_p^2 = .532$. On average, the increase in EMG amplitude of the FCR and ECR muscles ranged between 91%–105% and 29%–54% of the initial values, respectively (Figure 3b). Similar outcomes were found for EMG MdPF for both FCR and ECR muscles. A main effect of time was observed on these spectral measures, FCR: $F(4, 40) = 8.56$, $p < .0001$, $\eta_p^2 = .461$; ECR: $F(4, 10) = 23.38$, $p < .0001$, $\eta_p^2 = .70$, with MdPF of the FCR and ECR decreasing 16%–18% and 24%–26% of the initial values, respectively (Figure 3c). There were no significant main effects of task or gender or their two-way interactions on the EMG RMS or MdPF values for either arm muscles.

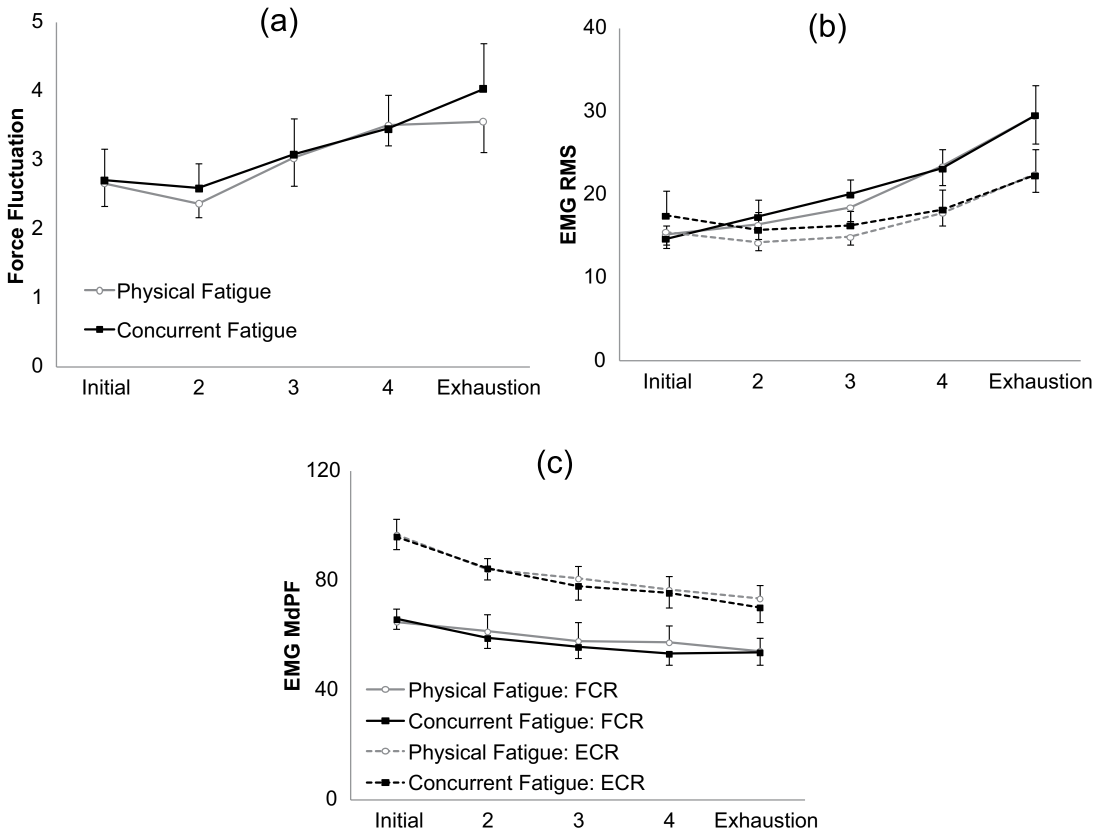

Figure 3. Changes in (a) joint steadiness, (b) electromyography (EMG) root mean squared (RMS) values of flexor carpi radialis (FCR; solid lines) and extensor carpi radialis (ECR; dotted lines) muscles, and (c) EMG median power frequency (MdPF) of FCR and ECR muscles during physical fatigue (gray lines) and concurrent fatigue (black lines) conditions across the five time epochs. Error bars represent standard error.

Performance and Self-Reports

Performance on the arithmetic task was significantly affected by task, $F(1, 10) = 10.98$, $p = .008$, $\eta_p^2 = .523$, with the concurrent fatigue condition resulting in poorer performance, that is, fewer correct responses, than the reference mental fatigue condition ($M = 15.7$, $SD = 5.6$ vs. $M = 27.3$, $SD = 14.6$). A separate two-way ANOVA to examine the effects of task (control vs. concurrent fatigue) and gender on RPE revealed no significant effects of either factor or their interactions. A three-way ANOVA to test the effects of task (3 levels: control vs. concurrent fatigue vs. reference mental arithmetic) × NASA TLX subscales (6 subscales) × gender revealed a significant main effect of task, $F(2, 20) = 45.16$, $p < .0001$, $\eta_p^2 = .819$, and subscales, $F(5, 50) = 10.77$, $p < .0001$, $\eta_p^2 = .519$, and a significant task × subscales interaction, $F(10, 100) = 26.34$, $p < .0001$, $\eta_p^2 = .725$. Post hoc comparisons between tasks on each subscale using Bonferroni correction revealed that perceived mental and temporal demand during physical fatigue condition were significantly lower than the other two conditions. In addition, the mental stressor induced greater frustration during the concurrent physical and mental fatigue condition compared to the physical fatigue condition alone. Finally, perceived physical demand was lowest for the reference mental fatigue condition alone compared to the other conditions. No significant differences were observed in the effort or performance subscales across the three task conditions (Figure 4). No differences due to gender were observed for any of the tasks or subscales.

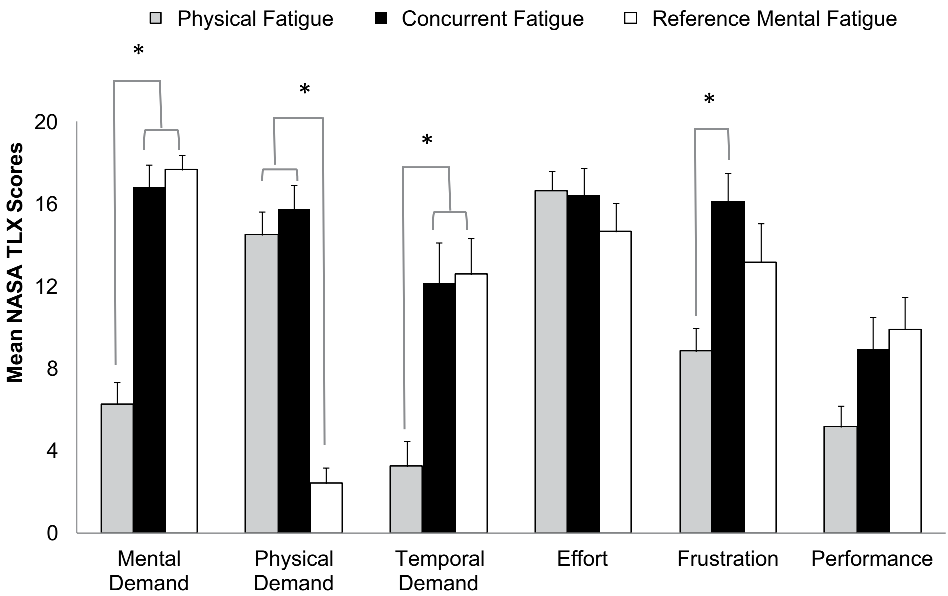

Figure 4. Interactive effects of task and NASA Task Load Index subscales on mean scores. Error bars represent standard error. The asterisk indicates a significant difference between the tasks in each subscale.

DISCUSSION

The present study investigated the effects of concurrent physical and mental fatigue on PFC activation during submaximal fatiguing handgrip exercises. The results indicated that concurrent physical and mental fatigue conditions were associated with lower Oxy-Hb levels in the bilateral PFC at exhaustion (i.e., at exercise cessation) compared to physical fatigue conditions. Using a neuroergonomic approach, we suggest that neural interference at the PFC may influence physical fatigue development during tasks that are associated with high cognitive demands.

PFC and Physical Fatigue

It is well established that a direct relationship exists between muscle activity and neural activity in cortical regions controlling motor function (Siemionow et al., 2000), indicating increased activation of cortical output neurons to generate descending motor commands (Dai et al., 2001). More recently, fNIRS studies targeting exercise cessation have suggested that PFC activation provides a useful hemodynamic indicator of central fatigue (Thomas & Stephane, 2008). In the present study, PFC activation increased over time for a set relative load and this increase has previously been attributed to either increased cerebral perfusion in response to increased metabolic by-products generated by the exercise or an increased central command to drive motor behavior. In a recent study Ogoh et al. (2010) demonstrated that 30% static handgrip exertions and related elevations in blood pressure did not alter dynamic cerebral autoregulation, thereby maintaining cerebral blood flow. In addition, Mintun et al. (2001) demonstrated that adequate tissue levels of oxygen could be maintained in hypoxia without a need for increased cerebral blood flow. Indeed, in the present study total hemoglobin levels during the handgrip exertions across both fatigue conditions (Figure 2a) remained relatively constant and were not significantly affected by time or task. Thus, the increase in PFC oxygenation over time can be attributed to additional neural activation required to generate downstream motor commands (i.e., concomitant increases in cerebral Oxy-Hb [Figure 2b] and EMG RMS values [Figure 3b] over time) to maintain motor performance (Figure 3a).

Previous fNIRS studies examining physical fatigue demonstrated a critical reduction in prefrontal oxygenation at point of exercise cessation

(Bhambhani et al., 2007; Nybo & Rasmussen, 2007). In the present study, cerebral oxygenation at the final time epoch (i.e., at exhaustion) did not decrease from the preceding time epoch. A supporting explanation could be the differences in determination of exhaustion points in these studies. Endurance time here was defined as the time at which the participant dropped more than 5% below the target without reattaining it compared to previous studies that focused at volitional exhaustion. Moreover, the present study focused on localized muscle fatigue of smaller arm muscles in contrast to whole-body fatigue (that is often seen with cycling and rowing exercises) that recruit larger muscles of the lower extremity. Of note, the reticular-activating hypofrontality (RAH) model hypothesizes that the influence of exercise on brain activity is dependent on muscle mass, intensity, and duration (Dietrich & Audiffren, 2011). Thus, it is possible that the extent of the role of PFC in exercise cessation is dependent on the type of fatigue and/or protocol employed.

PFC and Mental Fatigue

Prolonged periods of cognitive processing lead to manifestation of mental fatigue, which is commonly determined by subjective fatigue assessments or decrements in performance (Helton et al., 2010; Marcora et al., 2009). Mental fatigue has been shown to increase activation of the PFC (Helton et al., 2010; Lorist, Boksem, & Ridderinkhof, 2005). Findings from our study suggest that during the reference mental fatigue condition, that is, no motor fatigue, Oxy-Hb remained relatively stable after an initial increase from the 1st time epoch, with a sudden drop at the last time epoch (Figure 3d). This decrease in Oxy-Hb could be characterized as either the onset of mental fatigue (Lorist et al., 2005) or learning due to continued task exposure (Ong, Russell, & Helton, 2013). Given that mental arithmetic is thought to use the visuospatial sketchpad module of working memory (Baddeley, 2003), neuroimaging studies have linked both the PFC and the parietal lobe to mental arithmetic processing (Rivera, Reiss, Eckert, & Menon, 2005). Thus, it is unclear if the PFC trends observed here would be similar to that occurring in the parietal lobe. Further investigation using whole head fNIRS is needed to explore the association between the two cortical regions during mental fatigue development.

Interaction of Physical and Mental Fatigue on Muscular Responses

Recent literature suggests that mental stress prior to (Marcora et al., 2009) or during physical fatigue exercises (Mehta & Agnew, 2012) can negatively affect muscle capacity. Mental fatigue did not affect endurance times and strength loss in the present study, which focused on sustained static contractions of a more executive muscle group, that is, handgrip, whereas previous studies employed intermittent contractions of more postural muscles, such as shoulders and lower extremities (Marcora et al., 2009; Mehta et al., 2012). It should be noted that the mental stressor exposure times in these studies were longer and ranged from 10–15 min to 90 min, compared to ~3 min employed in the present study. Thus, the influence of mental fatigue on endurance time during physical fatigue development is possibly task-dependent (i.e., muscle- and duration-specific). Given the lack of effect on endurance time, it is not surprising that mental fatigue did not affect muscle activity (i.e., force fluctuations, EMG RMS or MdPF).

Interaction of Physical and Mental Fatigue: Neural Interference in PFC

The present study adopted a neuroergonomic approach to examine the influence of mental fatigue on physical fatigue development using fNIRS. Although muscular responses showed no difference between both conditions, distinctive neural alterations during fatigue development attributed to mental fatigue were observed. Cerebral oxygenation in both conditions increased linearly; however, oxygenation levels during the concurrent fatigue condition were higher in the initial stages but lower at exhaustion when compared to the control despite comparable muscular output between the two fatigue conditions. Such reversal in relative magnitude of PFC activation between the two conditions highlights the influence of mental fatigue on central fatigue development. The initial increase in cortical activation may be explained by the additional cognitive processing needed to perform the mental arithmetic task when compared to the control. As discussed earlier, working memory tasks, such as mental arithmetic, have shown activation in the dorsolateral PFC (Ayaz et al., 2012; McKendrick et al., 2013; Rowe et al., 2000) similar to that observed with isometric motor tasks (Dettmers et al., 1996). At the 1st and 2nd time epochs, available cortical resources at the PFC were adequately distributed between both motor and cognitive processing. However, over time an increase in cortical resources required to maintain force output, evident from the rising Oxy-Hb levels in both conditions, may have affected the initial cortical distribution pattern between motor and cognitive processing sites to maintain their respective performances. A possible explanation is that lower PFC activation observed in the concurrent fatigue condition compared to the control at exhaustion is related to decreased cortical activity directed to the mental arithmetic task. Our result on the decline in cognitive performance in the concurrent fatigue condition compared to the reference mental fatigue condition supports this explanation. This outcome further strengthens our hypothesis that neural interference in the PFC exists during concurrent motor and cognitive processing that may impair either cognitive or motor performance, or both. Moreover, the result closely follows the RAH model that hypothesizes that the PFC, a seat of higher-order cognitive functioning, is the first region to be negatively influenced by exercise (Dietrich & Audiffren, 2011).

Lower PFC activation at exhaustion in the concurrent fatigue condition, relative to the control, may also be explained by a potential cortical redistribution to maintain comparable muscle output (i.e., time to exhaustion) to that observed in the control fatigue condition. Supporting this view, Liu et al. (2007) demonstrated a distinct shift of activation centers in the brain to maximize central command to muscles, to prolong motor performance or maintain the muscle output after fatigue sets in. Although this study was limited to monitoring activation of the PFC alone, it is likely that mental fatigue accelerated cortical redistribution during physical fatigue development. Future investigation that monitors multiple motor-related cortical regions during voluntary fatigue development can provide important clues that could support the premature "shifting of activation center" during more stressful conditions. This study also corroborates our argument that evaluating muscular responses *alone* may not provide a complete understanding on fatigue mechanisms and that simultaneous brain and body functions provide critical information on the contributions of both central and peripheral pathways of voluntary fatigue development.

Effects of Physical and Mental Fatigue on Self-Reports

Consistent with existing literature, findings obtained here indicate that compared to RPEs, the NASA TLX instrument is a more sensitive tool in identifying contributions of mental fatigue in overall perception of workload (Mehta & Agnew, 2011, 2013). Concurrent fatigue conditions in the present study were associated with greater mental challenge, increased time pressure, and higher frustration compared to the physical fatigue condition alone. However, perceived physical demand and effort, along with RPE, were similar across the control and concurrent fatigue conditions. These results do not align with the findings by Marcora et al. (2009), who suggested that mental fatigue limits exercise through higher perception of effort and that the anterior cingulate cortex is the potential site of interference. Dissimilarities in the nature of mental fatigue introduced and/or the type of physical fatigue being investigated (Marcora et al., 2009, investigated the effects of a prior 90-min cognitive task on whole-body fatigue using a cycling fatigue protocol) may account for the differences in the observed results between the two studies.

The purpose of this study was to evaluate the interaction of physical and mental fatigue via a neuroergonomic approach, that is, investigating both brain and body responses, using fNIRS (Parasuraman & Mehta, in press). Our results indicate that although muscular responses were comparable between conditions, PFC activity in the concurrent fatigue condition was initially higher than the physical fatigue condition, but at exhaustion it dropped below the control condition. Such dynamic PFC patterns can be attributed to resource allocation and/or limitation due to additional cognitive processing. Moreover, the decrease in PFC activity at exhaustion during the concurrent condition relative to the control condition may be indicative of potential cortical redistribution to maximize neural drive to the muscles, thus explaining similar physical performance between the two conditions. This has important implications in assessment of fatigue, particularly in the physical ergonomics domain. First, the influence of mental fatigue on physical performance has been shown to be task-dependent. Thus, traditional fatigue measures, such as endurance time, strength loss, EMG, or RPE, may vary in their sensitivity to assess physical and nonphysical interactions, depending on the task parameters. This is an important consideration, particularly evaluating tasks and environments that place high physical and cognitive strain on operators, such as surgeons performing long complex surgical operations or firefighters engaged in rescue operations. In addition, a neuroergonomic approach in conjunction with traditional physiological measures of endurance may also provide important information on enhancing cognition during exercise for maximum sports performance. Second, one of the common methods to delineate contributions of central and peripheral fatigue is electrical stimulation of the targeted muscle, which is not only invasive and uncomfortable for participants, but also does not represent voluntary capacity of workers. Noninvasive neuroergonomic methods, such as fNIRS employed in this study, can provide a suitable alternative to mapping brain functions during physical work. Further investigations are warranted that can address limitations encountered in this study, such as extending cortical mapping to more motor-related brain regions other than the PFC, employing longer duration of both physical and mental work to increase exposure to both stressors, and furthering the application to assess other occupationally relevant tasks.

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KEY POINTS

- Current research suggests that mental fatigue impairs motor performance and muscle capacity.
- Traditional fatigue indicators, such as endurance time, strength loss, and electromyography indicators, may not be sensitive to the influence of mental fatigue.
- The results suggest that neural interference in the prefrontal cortex during concurrent physical and mental work contributes to fatigue development.
- Compared to traditional fatigue evaluation, a neuroergonomic approach provides critical information on the contributions of both central and peripheral pathways of voluntary fatigue development.

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