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Prefrontal Hemodynamics of Physical Activity and Environmental Complexity During Cognitive Work

Ryan McKendrick, Northrop Grumman Aerospace Systems, Redondo Beach, California, **Ranjana Mehta**, Texas A&M University, College Station, **Hasan Ayaz**, Drexel University, Philadelphia, Pennsylvania, **Melissa Scheldrup** and **Raja Parasuraman**, George Mason University, Fairfax, Virginia

Objective: The aim of this study was to assess performance and cognitive states during cognitive work in the presence of physical work and in natural settings.

Background: Authors of previous studies have examined the interaction between cognitive and physical work, finding performance decrements in working memory. Neuroimaging has revealed increases and decreases in prefrontal oxygenated hemoglobin during the interaction of cognitive and physical work. The effect of environment on cognitive-physical dual tasking has not been previously considered.

Method: Thirteen participants were monitored with wireless functional near-infrared spectroscopy (fNIRS) as they performed an auditory 1-back task while sitting, walking indoors, and walking outdoors.

Results: Relative to sitting and walking indoors, auditory working memory performance declined when participants were walking outdoors. Sitting during the auditory 1-back task increased oxygenated hemoglobin and decreased deoxygenated hemoglobin in bilateral prefrontal cortex. Walking reduced the total hemoglobin available to bilateral prefrontal cortex. An increase in environmental complexity reduced oxygenated hemoglobin and increased deoxygenated hemoglobin in bilateral prefrontal cortex.

Conclusion: Wireless fNIRS is capable of monitoring cognitive states in naturalistic environments. Selective attention and physical work compete with executive processing. During executive processing loading of selective attention and physical work results in deactivation of bilateral prefrontal cortex and degraded working memory performance, indicating that physical work and concomitant selective attention may supersede executive processing in the distribution of mental resources.

Application: This research informs decision-making procedures in work where working memory, physical activity, and attention interact. Where working memory is paramount, precautions should be taken to eliminate competition from physical work and selective attention.

Keywords: mind–body interaction, biomechanics, anthropometry, work physiology, near-infrared spectroscopy (NIRS), attentional processes, cognition, working memory, neuroergonomics

Address correspondence to Ryan McKendrick, Research, Technology and Advanced Design, Northrop Grumman Aerospace Systems, Redondo Beach, CA, 90278, USA; e-mail: ryan.mckendrick@ngc.com.

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INTRODUCTION

Measuring the cognitive states of individuals doing physical and cognitive work is important but difficult. Cognitive work and physical work often co-occur, whether in everyday life when we "walk and talk" or in trained individuals, such as firefighters, search-and-rescue operators, and military service men and women, during routine job performance. In both casual activity and professional work, questionnaire-based methods of cognitive state assessment can be intrusive. Further, although diagnostic and non-invasive, traditional neuroimaging techniques are impractical due to size and cost (functional magnetic resonance imaging [fMRI]).

A potential solution to the difficulty of monitoring the cognitive states and brain dynamics elicited by cognitive-physical dual tasking is functional near-infrared spectroscopy (fNIRS). The use of fNIRS is safe, highly portable, user-friendly, and relatively inexpensive, with rapid application times and near-zero run-time costs (Villringer & Chance, 1997; Ayaz, Cakir, et al., 2012; Ferrari & Quaresima, 2012; Mehta & Parasuraman, 2013). The most commonly used form of fNIRS employs infrared light between 630 and 900 nm, introduced at the scalp to measure changes in cortical blood oxygenation as oxyhemoglobin converts to deoxyhemoglobin during neural activity, that is, the cerebral hemodynamic response. FNIRS uses these specific wavelengths of light to provide measures of cerebral oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) that are correlated with the blood oxygenation level dependence signal (Cui, Bray, Bryant, Glover, & Reiss, 2011; Sato et al., 2013) used in fMRI research.

Through monitoring prefrontal hemodynamics, fNIRS has been useful for measuring cognitive states under cognitive and physical load.

Tasks that manipulate cognitive load by increasing the number of stimuli, or stimulus and stimulus-response complexity, consistently report a positive linear relationship between brain activity and cognitive load (Abibullaev & An, 2012; Ayaz et al., 2011; Ayaz, Shewokis, et al., 2012; Bogler, Mehnert, Steinbrink, & Haynes, 2014; Derosière, Dalhoumi, Perrey, Dray, & Ward, 2014; Herff et al., 2014; Naseer & Hong, 2013; Schudlo & Chau, 2013; Solovey, Afergan, Peck, Hincks, & Jacob, 2015). However, in more extreme cognitive load situations, prefrontal activity is attenuated, producing a negative quadratic or "inverted-*u*" relationship between cognitive load and prefrontal activity (Durantin, Gagnon, Tremblay, & Dehais, 2014; McKendrick, Ayaz, Olmstead, & Parasuraman, 2014). Similarly, increases in physical demand have been shown to increase prefrontal cortex (PFC) activity (Mandrick et al., 2013); however, physical work that induces muscular impairment and exhaustion reduces HbO in the PFC (Bhambhani, Malik, & Mookerjee, 2007; González-Alonso et al., 2004; Jung, Moser, Baucsek, Dern, & Schneider, 2015; Mehta & Parasuraman, 2014; Nybo & Rasmussen, 2007; Schmit et al., 2015).

Concurrent cognitive and physical work produces complex effects on performance and prefrontal hemodynamics. Prior studies suggest that facilitation or inhibition of performance is dependent upon task type compatibility—for example, choice reaction-time subtasks benefit from the addition of a physical subtask (Tomporowski, 2003), and working-memory tasks incur costs (Blakely, Kemp, & Helton, 2016; Darling & Helton, 2014; Dietrich & Audiffren, 2011; Green, Draper, & Helton, 2014; Green & Helton, 2011). Changes in prefrontal hemodynamics appear to be dependent upon the comparison being made. To be specific, the addition of a cognitive task to a physical task requires a greater commitment of HbO to PFC to facilitate cognitive performance (Doi et al., 2013; Holtzer et al., 2011; Mandrick et al., 2013; Mehta, 2016; Mirelman et al., 2014). However, the addition of a physical task to a cognitive task reduces HbO in PFC (Beurskens, Helmich, Rein, & Bock, 2014; Mehta & Parasuraman, 2014; Mehta & Shortz, 2014). Effectively, concentrations of HbO in PFC during cognitive-physical dual tasking lie between those observed during a solitary physical task and those observed during a solitary cognitive task.

The reticular-activating hypofrontality (RAH) hypothesis (Dietrich & Audiffren, 2011) attempts to unify cognitive-physical dual-task effects on performance and the brain via a resource distribution hierarchy. The RAH hypothesis states that acute physical action and its required mental computations receive priority with regard to a limited supply of neural resources. Therefore, during competition with prefrontal executive processes, resources are redistributed from executive brain regions to action brain regions to maintain physical task performance. However, because previous work has predominantly focused on changes in HbO and not HbR, it remains ambiguous as to whether the addition of physical tasks induces a redistribution of resources, indexed by a reduction in total hemoglobin, or a deactivation of PFC, indexed by an increase in HbR and a decrease in HbO.

Previous studies of resource competition between cognitive and physical work have been conducted in controlled laboratory settings. However, a number of jobs that require cognitive-physical dual tasking do not occur in controlled settings. On the contrary, they often occur in complex environments. Such environments may require the identification of relevant stimuli, inhibition or resolution of distractor interference, and navigating around obstacles. These environmental demands would be expected to increase the resource demands of selective attention, executive processing, and motor planning. Attentional load theory (Lavie, Hirst, de Fockert, & Viding, 2004) parsimoniously accounts for the effects of perceptual distractors at different levels of perceptual and cognitive load; high perceptual load inhibits the perception of external distractors (i.e., early selection), and low perceptual load requires executive functions to resolve the interference of perceived distractors (i.e., late selection). Cognitively, the loading of working-memory subcomponents differentially affects distractor perception. High load from working-memory set maintenance inhibits distractor perception, and loading the cognitive control components of working memory increases distractor perception (Konstantinou, Beal, King, & Lavie, 2014; Lavie, 2010). What is not entirely clear is how attentional load theory interacts with the RAH hypothesis under conditions of physical activity and increased environmental complexity.

Examining the interaction between cognitive-physical dual tasking in natural environments is extremely difficult. However, the recent development of portable and wireless fNIRS systems now affords untethered measurements and wearable sensors (Ayaz et al., 2013; McKendrick, Parasuraman, & Ayaz, 2015). Portable, untethered measurement allows for concurrent acquisition of behavioral and hemodynamic measures of resource competition under physical activity and in naturalistic environments. Recently, mobile fNIRS was used to assess prefrontal differences in mental workload and situation awareness during real workload navigation between a smartphone and an augmented-reality wearable display (McKendrick et al., 2016). The neuroergonomic approach to resource assessment stresses the integration of cognitive neuroscience, cognitive psychology, and human factors methodologies to study the brain in relation to performance at work and in everyday settings (Parasuraman & Rizzo, 2008). In accordance with this approach, the current study monitored lateral prefrontal hemodynamics with wireless fNIRS during performance of an auditory working-memory task while sitting, walking in an empty hall, or walking across a busy college campus to explore the interactions between cognitive-physical dual tasking in natural environments.

METHOD

Participants

Thirteen George Mason University students (four females, nine males) were recruited. Participants ranged in age between 19 and 31 years with an average age of 22 years. All participants reported being right-handed and having normal or corrected-to-normal vision. All participants also reported having no known history of cardiovascular health problems or of taking prescription drugs that alter neural or cognitive function. Failure on any of these criteria would have excluded the participant from study participation. This research complied with the American Psychological Association Code of Ethics, and prior to participation, each student gave informed consent via a form approved by the George Mason University Institutional Review Board.

Tasks

Auditory 1-back task. An auditory working-memory task was the primary cognitive task performed by participants throughout the study. Stimuli consisted of tone triplets randomly composed from fundamental frequencies of 493.88, 554.36, 698.45, and 880 Hz and were presented via Bluetooth in-ear headphones. The tones were created from bandpass-filtered white noise and a tone overlay. Three tones selected at random were presented sequentially to compose a triplet. Each tone was presented at 75 db and lasted for 800 ms with a 3-ms ramp-up/ramp-down with no delay between triplet tones. The triplets (all three sequential tones) were presented randomly in one of three spatial locations: left (100% left ear sound distribution), right (100% right ear sound distribution), and center (balanced sound distribution between both ears). Five triplets were presented for each block of trials with a 3-s intertrial interval.

Participants were asked to compare the triplet they had just heard with the triplet they had previously heard which was considered one trial. If the tones composing the two triplets were of the same frequencies and presented in the same temporal sequence, the trial was considered a match. The spatial location or sound distribution the triplets were presented in was to be ignored and did not determine comparison accuracy. At the end of a block, participants were prompted by the experimenter to verbally indicate how many matching trials they heard. The experimenter recorded the response on the tablet computer running the stimuli presentation software by pressing the keyboard numeral corresponding to the participant response. Participants were immediately given positive or negative auditory feedback regarding the accuracy of their response.

Procedures

FNIRS setup. Participants were seated and were asked to remove any makeup from their

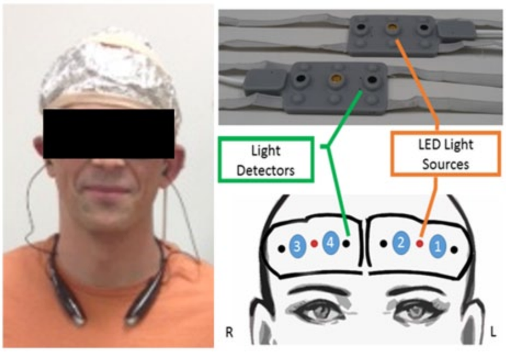

Figure 1. Participant wearing battery-operated wireless functional near-infrared spectroscopy (fNIRS) sensor over the forehead. Wireless fNIRS sensor pads (right, top) and placement sketch (right, bottom) with four optodes identified between light source and detectors.

forehead with an alcohol pad and/or to adjust their hair prior to affixing the fNIRS neuroimaging device (FNIR Devices LLC, MD; Model 1100W). The separate sensor pads were placed approximately 3 cm above the participant's brow and centered approximately 9 cm laterally from the midline of the participant's forehead. The positioning was intended to capture hemodynamic changes in bilateral PFC (Figure 1). Drawstrings attached to the sensor pads were used to prevent the pads from moving once positioned on the participant. A 9-cm-wide self-adhesive bandage of length approximately the circumference of the participant's head was folded widthwise and secured around the participant's head across the brow just below the fNIRS sensor pads. Next, a sheet of aluminum foil approximately half the circumference of the participant's head and folded widthwise was form fitted over the bandage and fNIRS sensor pads. Care was taken to ensure that the fNIRS sensor pads were fully encapsulated by the aluminum foil sheet to ensure that while imaging in sunlight, infrared light from the sun would not contaminate the fNIRS signal.

Once the foil was affixed to the participant, two more self-adhesive bandages of length approximately the circumference of the participant's head were used. One bandage folded twice widthwise was wrapped around the participant's head just below the fNIRS sensor pads, over the participant's brow and over the aluminum foil. The second bandage was folded once widthwise and wrapped around the participant's head just above the fNIRS sensor pads and over the foil. These bandages were used to ensure that the foil did not shift during walking. During bandage placement, special care was taken to minimize constrictive pressure over the fNIRS sensor as initial pilot tests showed this pressure to be extremely uncomfortable for the participants after only a few minutes of walking. Once the sensors, foil, and bandages were positioned, the fNIRS device was turned on and the signal was gain adjusted for signal quality (i.e., light intensity at the detector higher than the analog-to-digital converter limit). When the signal was deemed adequate, the participant was asked to put the fNIRS transmitter in his or her pocket.

Experimental paradigm. Once the fNIRS imaging setup was complete, participants were given Bluetooth in-ear headphones and were instructed to place the ear buds in their ears. Prior to this step, the ear buds were cleaned with alcohol pads. If the ear buds did not fit, a new-size bud was used to optimize the setup for the participant. Once the headphones were set up, participants were introduced to the auditory 1-back task described earlier. Participants performed one practice block to ensure they understood and could successfully perform the task (i.e., report the correct number of matches at the end of a block). If after one practice block participants were unable to accurately report the number of matching trials, a second practice block was given. No participant required more than two practice blocks in order to understand and accurately perform the auditory task. Participants then performed eight blocks of four trials per block of the auditory 1-back task. The first two blocks were performed while sitting in a quiet room. The next two blocks were performed while walking through an empty hallway. Participants walked the hallway and made right turns at each junction to facilitate a circular walking path.

After that, the participants moved outside and two blocks were performed while walking around a moderately busy college campus. Participants were instructed to walk from one building entrance to another. They were allowed to reach the target waypoint via a path of their choosing. The outdoor environment included hills, stairs, and other students walking around. The experimental sessions were conducted between 10 a.m. and 2 p.m. during the spring and summer semesters. The final two blocks were performed while sitting in the same room as the first two blocks. Each block was approximately 120 s in duration.

FNIRS signal processing. For each participant, the fNIRS data for each task trial were extracted using time synchronization markers for stimulus onset and participant response. These raw light intensity time series (4 optodes × 2 wavelengths) were low-pass filtered with a finite impulse response, linear phase filter with order 20, and cutoff frequency of 0.1 Hz to attenuate high-frequency noise, respiration, and cardiac cycle effects (Ayaz et al., 2011). Each participant's data were checked for any potential saturation (when light intensity at the detector was higher than the analog-to-digital converter limit) and motion artifact contamination by means of a coefficient of variation-based assessment (Ayaz, Izzetoglu, Shewokis, & Onaral, 2010). Relative concentration time series of HbO and HbR for each of four optodes and each trial were calculated using the modified Beer-Lambert law as described in Ayaz, Cakir, et al. (2012) to estimate the total photon path length of the different wavelengths of back-scattering light.

Analyses

Generalized and linear mixed-effects models. All forthcoming statistical tests employ either linear mixed-effects or generalized linear mixed-effects models implemented in R (R Core Team, 2012) via lme4 (Bates, Maechler, Bolker, & Walker, 2014). Linear mixed-effects estimates were computed with restricted maximum likelihood, and generalized linear mixed estimates were computed with maximum likelihood and binomial link functions. Denominator degrees of freedom and *p* values were estimated via Sattherwaite corrections implemented via lmerTest (Kuznetsova, Brockhoff, & Christensen, 2013). These models offer several advantages as extensions of the general linear model, such as analysis of binomial outcomes, treatment of effects as simultaneously fixed and random, hierarchical modeling, analysis of unbalanced designs, and robustness to missing data (Baayen, Davidson, & Bates, 2008; Demidenko, 2013; Jaeger, 2008; Pinheiro & Bates, 2000; Verbeke & Molenberghs, 2009).

Fixed- and random-effects selection. The Bayesian information criterion (BIC; Schwarz, 1978) was used to select the fixed and random effects in the final models for each dependent variable. Competing models were constructed by adding potentially meaningful random and fixed effects to a null model. The null model was specified in each case as having no fixed effects and a random effect of participant intercept. All competing models were estimated with maximum likelihood to allow for testing of fixed effects. The competing models were tested simultaneously with BIC, and the strength of evidence criterion described by Kass and Raftery (1995) was employed. In the procedure, deviations of greater than 2 BIC are viewed as a meaningful difference. The final model was selected based on having the lowest BIC, with no other models of interest having a BIC deviance of less than 2.

Multiple comparisons corrections. In all forthcoming analyses of fNIRS data, multiple comparisons were corrected for across hypotheses and optodes but within chromophores by adjusting the *p* value criteria for each effect with false discovery rate (FDR) corrections. Controlling for FDR can increase statistical power relative to correcting for multiple comparisons via controlling for the familywise error rate (Benjamini & Hochberg, 1995). The Benjamini-Hochberg FDR procedure, employed here for controlling the FDR, is adaptive in that the threshold for rejecting the null hypothesis is dependent on the size of the initial *p* value and the number of hypotheses tested (Benjamini & Hochberg, 1995; Lindquist, 2008). Adjustments were made with alpha set to 0.05 in the Benjamini-Hochberg equation.

RESULTS

Motion Artifacts

To measure the relationship between unrestricted motion and the wireless fNIRS signal, HbO time series were submitted to a generalized linear mixed-effects regression. The tested model for each optode specified physical condition (i.e., sitting, walking, and walking outdoors) as the fixed effect and participant intercept and uncorrelated time series slopes as the random effects. The inclusion of random intercepts and slopes in the selected model suggests that meaningful variance was accounted for by assuming that log odds ratio estimates varied randomly across participants, and the degree to which this was altered across the time series was unrelated to participant's log odds ratio estimates. After accounting for the participant-based random effects, there was a parsimonious effect of physical condition. Overall, the log odds of rejecting a sample at any point were very low. The log odds of rejecting a sample were increased across the PFC while walking outdoors and in the left PFC while walking. These effects were likely caused by increased orienting and head movements required of moving through an environment. However, the overall effect on signal quality was negligible. Complete model estimates are presented in Table 1.

TABLE 1: Optode Signal-to-Noise Ratio

Fixed Effect	*B*	*Z* Value
Left lateral PFC		
Sit	–14.91	–7.55***
Walk	0.89	4.60***
Walkout	1.38	7.94***
Left medial PFC		
Sit	–8.26	–3.72***
Walk	2.20	8.94***
Walkout	3.59	15.47***
Right medial PFC		
Sit	–5.76	–4.34***
Walk	–0.01	–0.12
Walkout	0.83	10.00***
Right lateral PFC		
Sit	–13.99	–5.48***
Walk	–0.17	–1.36
Walkout	0.24	2.28*

Note. PFC = prefrontal cortex.
*$p < .05$. **$p < .01$. ***$p < .001$.

Auditory 1-Back Performance

To measure the effects of sitting, walking, and walking outdoors on auditory working memory, auditory 1-back performance was submitted to a generalized linear mixed-effects regression. The tested model specified physical condition (i.e., sitting, walking, and walking outdoors) as the fixed effect and participant intercept as the random effect. The inclusion of random intercepts suggests that meaningful variance was accounted for by assuming that log odds ratio estimates of auditory 1-back accuracy while sitting varied randomly across participants. After accounting for the participant-based random effects, there was a parsimonious effect of physical condition. While sitting, individuals accurately performed the 1-back task, $b = 2.31$, $SE = 0.41$, $p < .001$. Relative to sitting, walking did not significantly alter performance, $b = -0.64$, $SE = 0.35$, $p = .07$. However, walking outdoors did significantly reduce auditory working memory performance (Figure 2), $b = -0.98$, $SE = 0.33$, $p < .01$.

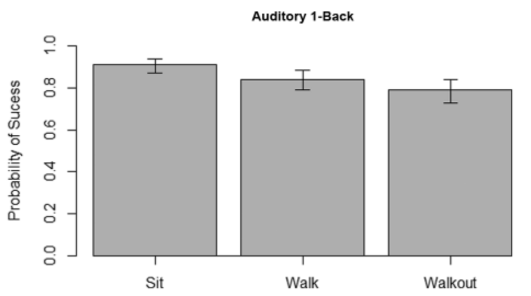

Figure 2. Probability of a correct response in the auditory 1-back task across conditions of sitting, walking indoors, and walking outdoors. Error bars represent standard errors of the beta coefficient estimate.

Hemodynamic Effects

To measure the effects of sitting, walking, and walking outdoors on lateral prefrontal hemodynamics, HbO and HbR time series were submitted to a linear mixed-effects regression. The most parsimonious model in each optode specified physical condition (i.e., sitting, walking, and walking outdoors), accuracy, and the interaction between condition and accuracy as the fixed effects. Participant intercept and participant slopes as a function of experiment block were specified as random effects. The inclusion of random intercepts and slopes suggests that participants differed in their mean

TABLE 2: Hemodynamic Effects: Left Lateral Prefrontal Cortex

	HbO		HbR	
Fixed Effect	*B*	*t*	*B*	*t*
Sit	0.04	0.65	–0.19	–3.89**
Walk	–0.21	–3.09**	–0.25	–5.21***
Walkout	–0.24	–3.51**	–0.02	–0.47
Sit - walk	0.26	27.14***	0.06	10.64***
Sit - walkout	0.29	32.27***	–0.17	–29.32***
Walk - walkout	0.03	2.94**	–0.23	–36.62***
Correct	–0.12	–1.69	–0.16	–3.41**
Incorrect	–0.16	–2.29	–0.14	–2.98*
Incorrect - correct	–0.04	–5.08***	0.02	3.80***
Sit : Correct	0.02	0.28	–0.16	–3.21 **
Walk : Correct	–0.07	–0.95	–0.31	–6.38***
Walkout : Correct	–0.30	–4.37***	–0.03	–0.60
Sit - walk : Correct	0.08	9.86***	0.15	28.11***
Sit - walkout : Correct	0.32	38.99***	–0.13	–24.13***
Walk - walkout : Correct	0.24	24.51***	–0.28	–45.75***
Sit : Incorrect	0.07	1.01	–0.22	–4.54***
Walk : Incorrect	–0.36	–5.16***	–0.20	–4.01**
Walkout : Incorrect	–0.18	–2.63*	–0.02	–0.34
Sit - walk : Incorrect	0.43	25.67***	–0.03	–2.36*
Sit - walkout : Incorrect	0.25	16.18***	–0.20	–20.63***
Walk - walkout : Incorrect	–0.18	–10.42***	–0.18	–16.59***
Incorrect - correct : Sit	0.05	4.11***	–0.07	–8.37***
Incorrect - correct : Walk	–0.29	–19.86***	0.11	11.95***
Incorrect - correct : Walkout	0.12	9.04***	0.01	1.54

Note. HbO = oxygenated hemoglobin; HbR = deoxygenated hemoglobin. Hyphens denote contrasting levels, and colons denote the grouping level of the interaction variable.
*$p < .05$. **$p < .01$. ***$p < .001$.

hemodynamic response and the change in that response over time. Specific comparisons for fixed effects are presented next.

Left lateral PFC. The results of the analysis of hemodynamic effects in left lateral PFC are summarized in Table 2 and visualized in Figure 3. In left lateral PFC, there is a reduction in HbR during performance of the auditory 1-back task while sitting. Adding walking to the auditory 1-back task reduced total hemoglobin during correct blocks and greatly reduced HbO during incorrect blocks. Further, increasing the complexity of the environment in which the task was performed reduced the hemodynamic response (i.e., decreased HbO and increased HbR). The reduced hemodynamic response occurred relative to both sitting and walking as well as during correct and incorrect blocks, the one caveat being that an increase in total hemoglobin occurred for incorrect blocks relative to walking. Finally, it is worth noting that relative to correct blocks, incorrect blocks were associated with a reduction in the hemodynamic response.

Left medial PFC. The results of the analysis of hemodynamic effects in left medial PFC are summarized in Table 3 and visualized in Figure 4. In left medial PFC, HbR decreased during performance of the auditory 1-back task while sitting but only for correct blocks. Performing the task while walking increased the hemodynamic response

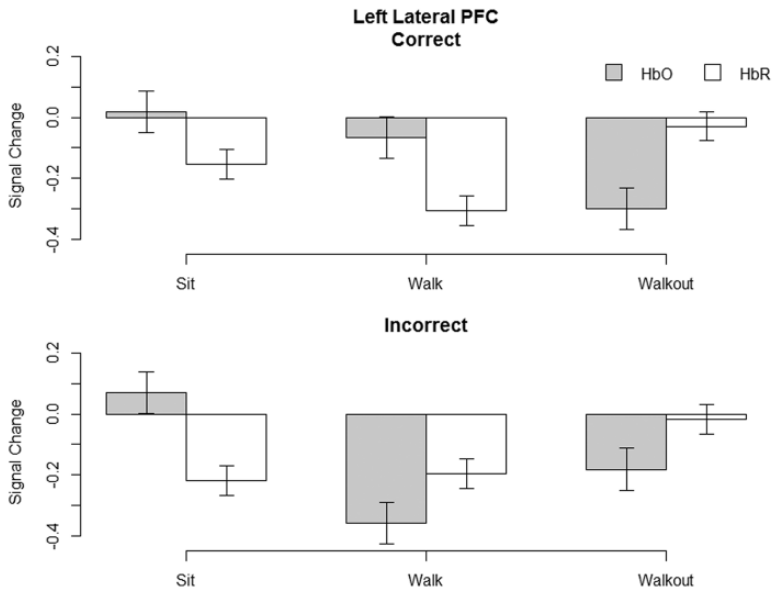

Figure 3. Left lateral prefrontal cortex (PFC) signal change in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) as a function of experimental condition and auditory 1-back block accuracy. Error bars represent standard errors of the beta coefficient estimate. Incorrect estimates for sit condition based on 19 trials and 2,280 functional near-infrared spectroscopy (fNIRS) samples; walk based on 17 trials and 2,040 fNIRS samples; walkout based on 22 trials and 2,640 fNIRS samples.

during correct blocks and decreased total hemoglobin during incorrect blocks. Further, relative to walking indoors, increasing the environmental complexity in which the task was performed decreased the hemodynamic response during correct blocks and increased the hemodynamic response during incorrect blocks.

Right medial PFC. The results of the analysis of hemodynamic effects in right medial PFC are summarized in Table 4 and visualized in Figure 5. In right medial PFC, HbR decreased during performance of the auditory 1-back task while sitting. Correctly performing the task while walking was associated with an increase in total hemoglobin, with the largest change occurring for HbO; incorrect performance was associated with a reduction in HbO. Further, relative to walking indoors, increasing the environmental complexity in which the task was performed was associated with a decrease in total hemoglobin during correct blocks and an increase in the hemodynamic response during incorrect blocks. Finally, it is worth noting that task accuracy was predominantly associated with changes in total hemoglobin.

Right lateral PFC. The results of the analysis of hemodynamic effects in right lateral PFC are summarized in Table 5 and visualized in Figure 6. In right lateral PFC there is a reduction of HbR during performance of the auditory 1-back task while sitting. Adding walking to the auditory 1-back task further reduced HbR during correct blocks and reduced the hemodynamic response during incorrect blocks. Increasing the complexity of the task environment reduced the hemodynamic response during correct blocks, and increased HbR during incorrect blocks.

DISCUSSION

Cognitive-physical dual tasking is prevalent in everyday life. Most of us experience it during mundane tasks, such as grocery shopping, when we meander up and down the store aisles while

TABLE 3: Hemodynamic Effects: Left Medial Prefrontal Cortex

	HbO		HbR	
Fixed Effect	*B*	*t*	*B*	*t*
Sit	–0.01	–0.13	–0.24	–2.32
Walk	–0.10	–1.12	–0.39	–3.75**
Walkout	–0.09	–1.06	–0.32	–3.06*
Sit - walk	0.09	3.29***	0.15	9.19***
Sit - walkout	0.08	3.33***	0.08	5.12***
Walk - walkout	–0.01	–0.28	–0.07	–5.19***
Correct	–0.05	–0.55	–0.32	–3.00*
Incorrect	–0.09	–1.00	–0.33	–3.10*
Incorrect - correct	–0.04	–2.05	–0.01	–1.04
Sit : Correct	–0.10	–1.15	–0.30	–2.86*
Walk : Correct	0.04	0.48	–0.43	–4.09**
Walkout : Correct	–0.09	–0.97	–0.21	–2.03
Sit - walk : Correct	–0.14	–8.94***	0.13	13.22***
Sit - walkout : Correct	–0.02	–0.99	–0.09	–9.24***
Walk - walkout : Correct	0.13	7.37***	–0.21	–20.35***
Sit : Incorrect	0.08	0.80	–0.19	–1.77
Walk : Incorrect	–0.24	–2.59	–0.36	–3.38*
Walkout : Incorrect	–0.10	–1.12	–0.43	–4.06**
Sit - walk : Incorrect	0.32	6.32***	0.17	5.55***
Sit - walkout : Incorrect	0.18	3.85***	0.24	8.47***
Walk - walkout : Incorrect	–0.14	–3.27**	0.07	–2.61**
Incorrect - correct : Sit	0.18	4.57***	0.11	4.64***
Incorrect - correct : Walk	–0.28	–7.90***	0.07	3.08***
Incorrect - correct : Walkout	–0.02	–0.57	–0.22	–12.23***

Note. HbO = oxygenated hemoglobin; HbR = deoxygenated hemoglobin. Hyphens denote contrasting levels, and colons denote the grouping level of the interaction variable.
*$p < .05$. **$p < .01$. ***$p < .001$.

trying to maintain those last few grocery list items in working memory. In other situations, the ability to cognitive-physical dual task has more severe consequences. Firefighters and military infantry must make complex decisions and navigate difficult terrain—all while laden with heavy gear and equipment. Currently little is known about how physical tasks affect the brain activity underlying cognition in nonlaboratory settings. The present study used mobile fNIRS to examine how walking and walking in increasingly complex environments alters lateral prefrontal activity while performing an auditory working memory task.

We found that wireless fNIRS signal quality was minimally affected by walking. Signal quality was significantly reduced by an increased number of motion artifacts when individuals walked outdoors. This difference is likely due to the increased number of head movements made while walking in a more complex environment. Even though the signal was reduced while walking outdoors, this reduction was minimal and not enough to preclude the use of the signal in further analysis or future naturalistic studies.

Behaviorally, individuals found the auditory 1-back task easy, responding correctly 91% of the time. Hemodynamically, there was bilateral sensitivity and specificity across the experimental conditions at the most lateral measurement sights. Consistent with previous studies of working

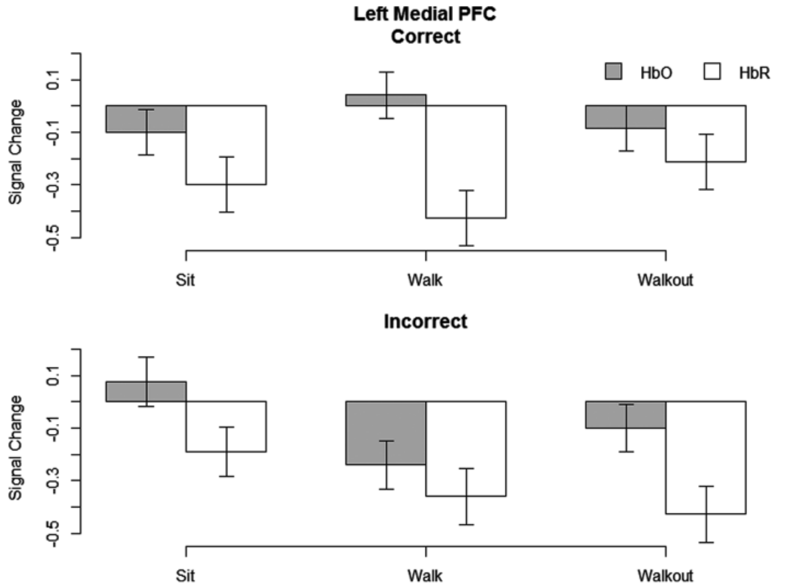

Figure 4. Left medial prefrontal cortex (PFC) signal change in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) as a function of experimental condition and auditory 1-back block accuracy. Error bars represent standard errors of the beta coefficient estimate. Incorrect estimates for sit condition based on 19 trials and 2,280 functional near-infrared spectroscopy (fNIRS) samples; walk based on 17 trials and 2,040 fNIRS samples; walkout based on 22 trials and 2,640 fNIRS samples.

memory, brain activity increased (e.g., reduction in HbR) during 1-back performance (Braver et al., 1997; Cohen et al., 1997) relative to baseline, verifying that these measurement sites were sensitive to the cognitive task.

The addition of physical work, in this case, walking, to the auditory 1-back task reduced the concentrations of HbO and HbR in left lateral PFC, with a similar but weaker trend observed in right lateral PFC, overall representing a decrease in total hemoglobin. This finding was associated with a marginal decrease in working-memory performance while walking. A reduction of total hemoglobin is effectively a reduction in the amount of resources available to lateral PFC for cognitive work during concurrent physical work. The reduction in total hemoglobin aligns with the RAH hypothesis (Dietrich & Audiffren, 2011), which predicts that resources are redistributed from executive-processing regions to help cope with the resource requirements of physical action. Previous support for the RAH hypothesis has focused on decrements in HbO with physical work (Bhambhani et al., 2007; González-Alonso et al., 2004; Jung et al., 2015; Mehta & Parasuraman, 2014; Nybo & Rasmussen, 2007; Schmit et al., 2015). However, changes in HbO alone cannot differentiate between a redistribution of resources and a reduction in the hemodynamic response. A concomitant reduction in both HbO and HbR better favors a redistribution of resources interpretation, as changes in the hemodynamic response involve inverse changes in HbO and HbR. Therefore, our observation of a concurrent reduction in HbR and HbO suggests that low-intensity physical work, such as walking, induces a redistribution of neural resources, not a deactivation of lateral PFC.

It is worth noting that due to the imaging setup used in the current study, we could not determine if the reduction in neural resources in lateral PFC was accompanied by concurrent increases in resources to other areas of the brain. However, given the increase in brain activity in medial PFC with the onset of walking, we can suggest that an increase in blood flow to the

TABLE 4: Hemodynamic Effects: Right Medial Prefrontal Cortex

	HbO		HbR	
Fixed Effect	*B*	*t*	*B*	*t*
Sit	–0.02	–0.37	–0.21	–3.93**
Walk	–0.01	–0.19	–0.16	–2.98*
Walkout	0.00	0.04	–0.27	–5.01***
Sit - walk	–0.01	–0.80	–0.05	–6.16***
Sit - walkout	–0.03	–2.03	0.06	7.58***
Walk - walkout	–0.02	–1.08	0.11	13.10***
Correct	0.01	0.22	–0.20	–3.65**
Incorrect	–0.04	–0.56	–0.24	–4.31**
Incorrect - correct	–0.05	–4.24***	–0.04	–5.23***
Sit : Correct	–0.09	–1.38	–0.23	–4.16**
Walk : Correct	0.17	2.73*	–0.16	–2.93*
Walkout : Correct	–0.04	–0.69	–0.21	–3.82**
Sit - walk : Correct	–0.26	–22.06***	–0.07	–9.33***
Sit - walkout : Correct	–0.04	–3.91***	–0.02	–2.75**
Walk - walkout : Correct	0.22	16.55***	0.05	6.07***
Sit : Incorrect	0.04	0.63	–0.20	–3.65**
Walk : Incorrect	–0.20	–3.02**	–0.17	–2.99*
Walkout : Incorrect	–0.05	–0.69	–0.34	–6.15***
Sit - walk : Incorrect	0.24	9.66***	–.04	–2.42*
Sit - walkout : Incorrect	–0.01	–0.37	0.14	9.81***
Walk - walkout : Incorrect	–0.25	–10.12***	0.17	11.70***
Incorrect - correct : Sit	0.13	6.93***	0.03	2.21*
Incorrect - correct : Walk	–0.37	–17.52***	–0.01	–0.46
Incorrect - correct : Walkout	–0.09	–5.05***	–0.13	–11.71***

Note. HbO = oxygenated hemoglobin; HbR = deoxygenated hemoglobin. Hyphens denote contrasting levels, and colons denote the grouping level of the interaction variable.
$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

lower extremities did not produce a systematic reduction in resources throughout cortex.

The addition of environmental complexity, in this case, the addition of auditory and visual distractors to the cognitive-physical dual task, reduced the concentration of HbO and increased the concentration of HbR at the most lateral measurement sites. This specific pattern of chromophore change represents a reduction in the hemodynamic response and brain activity at these measurement sites. Further, auditory working-memory performance during the environmentally complex dual task was reduced compared to performance on the cognitive subcomponent performed in isolation. Previous research has shown that irrelevant speech can have negative effects on short-term memory (Banbury, Macken, Tremblay, & Jones, 2001; Hughes, Tremblay, & Jones, 2005). However, in this instance, there is insufficient evidence to support processing of irrelevant speech as the cause of the decrement in working-memory performance. Processing of irrelevant speech and resolution of this distractor interference by late selective attention should have increased brain activity in lateral PFC (Badre & Wagner, 2007). However, the opposite was observed: Bilateral prefrontal activity decreased as evidenced by a decrease in HbO and concurrent increase in HbR.

Similar deactivations of PFC to those observed here have also been reported during

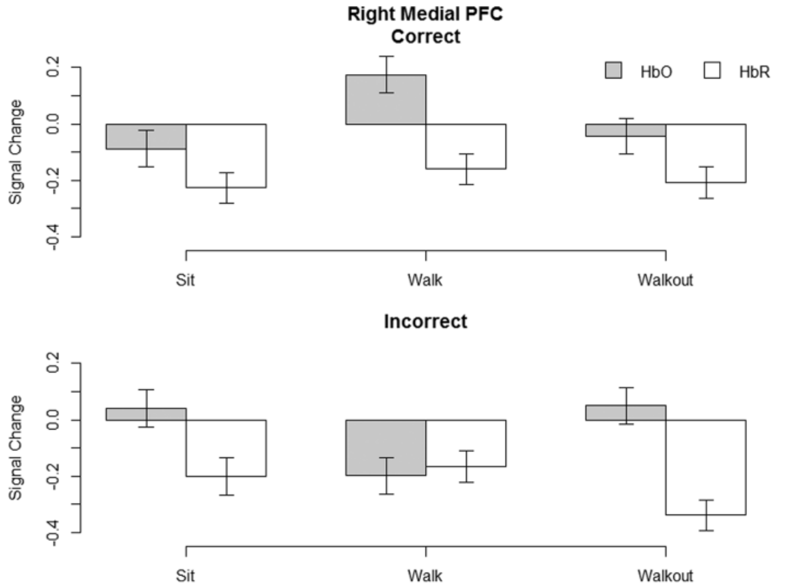

Figure 5. Right medial prefrontal cortex (PFC) signal change in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) as a function of experimental condition and auditory 1-back block accuracy. Error bars represent standard errors of the beta coefficient estimate. Incorrect estimates for sit condition based on 19 trials and 2,280 functional near-infrared spectroscopy (fNIRS) samples; walk based on 17 trials and 2,040 fNIRS samples; walkout based on 22 trials and 2,640 fNIRS samples.

increased perceptual load (Xu, Monterosso, Kober, Balodis, & Potenza, 2011) and likely result from inhibition of distractor interference by early selective attention, commensurate with attentional load theory (Lavie et al, 2004). Perceptual load was likely increased in the walking-outdoors condition due to perceptual demands of walking in an obstacle-laden environment. Obstacles in this instance included immobile objects as well as mobile students. The negative effect of obstacle and attentional load coheres with previous research on running and tone counting (Blakely et al., 2016).

This work represents an initial step toward understanding the effects that environment and mobility have on the brain activity underlying cognition. However, the following limitations should be addressed in future work. Specifically, developments need to be made with fNIRS technology so that whole head imaging can be performed while individuals are mobile. This method is needed to provide direct evidence that total hemoglobin reduction in the PFC is related to a redistribution of those resources to posterior cortical regions. Direct evidence of a relationship between attentional load and prefrontal deactivation is also needed, and authors of future work should test these effects explicitly and relate them to our observed effects regarding environmental complexity. Finally, the physical and cognitive tasks used here are basic in nature; there are instances when the complexity and workload of both the physical and cognitive task are greater than what we used in our study. Therefore, the complexity and workload of the interacting cognitive and physical tasks should be systematically manipulated in future studies to determine if these alterations moderate the presently observed effects of cognitive-physical dual tasking.

CONCLUSION

Our results speak to the usefulness of wireless fNIRS to non-invasively measure cognitive states in naturalistic settings as well as the usefulness of neuroergonomics in studying naturalistic behavior

TABLE 5: Hemodynamic Effects: Right Lateral Prefrontal Cortex

	HbO		HbR	
Fixed Effect	*B*	*t*	*B*	*t*
Sit	0.08	1.16	–0.13	–3.13**
Walk	0.01	0.06	–0.12	–2.90*
Walkout	–0.09	–1.29	–0.04	–0.97
Sit - walk	0.08	6.97***	–0.01	–1.53
Sit - walkout	0.18	17.69***	–0.09	–16.54***
Walk - walkout	0.10	8.52***	–0.08	–12.90***
Correct	0.02	0.30	–0.12	–3.05*
Incorrect	–0.03	–0.34	–0.07	–1.62
Incorrect - correct	–0.05	–4.99***	0.06	11.66***
Sit : Correct	0.10	1.37	–0.12	–2.90*
Walk : Correct	0.08	1.15	–0.18	–4.42***
Walkout : Correct	–0.12	–1.63	–0.07	–1.80
Sit - walk : Correct	0.02	1.66	0.06	12.76***
Sit - walkout : Correct	0.22	25.27***	–0.04	–9.82***
Walk - walkout : Correct	0.20	19.92***	–0.11	–19.91***
Sit : Incorrect	0.08	0.94	–0.14	–3.33**
Walk : Incorrect	–0.08	–1.01	–0.06	–1.36
Walkout : Incorrect	–0.07	–0.95	–0.01	–.013
Sit - walk : Incorrect	0.14	6.96***	–0.08	–7.36***
Sit - walkout : Incorrect	0.14	7.67***	–0.13	–13.75***
Walk - walkout : Incorrect	–0.01	–0.26	–0.05	–4.66***
Incorrect - correct : Sit	–0.03	–2.09	–0.02	–2.50*
Incorrect - correct : Walk	–0.16	–8.84***	0.12	13.04***
Incorrect - correct : Walkout	0.05	3.38***	0.07	8.88***

Note. HbO = oxygenated hemoglobin; HbR = deoxygenated hemoglobin. Hyphens denote contrasting levels, and colons denote the grouping level of the interaction variable.
**p* < .05. ***p* < .01. ****p* < .001.

and brain function. As such, in accordance with both the RAH hypothesis and attentional load theory, the presence of high processing demands from physical work and increased attentional load deprioritized executive functions (e.g., working memory) in the mental-resource hierarchy. Therefore, based on performance and brain activity, performing cognitive work prior to physical work is more optimal than performing cognitive and physical work simultaneously. Future work needs to directly assess the major hypotheses presented here regarding redistribution of prefrontal resources and changes in attentional load underlying the effects observed from increases in environmental complexity. Further, other moderating variables, such as complexity and workload level of the physical and cognitive tasks as well as individual differences in cognitive capacities, should be explored.

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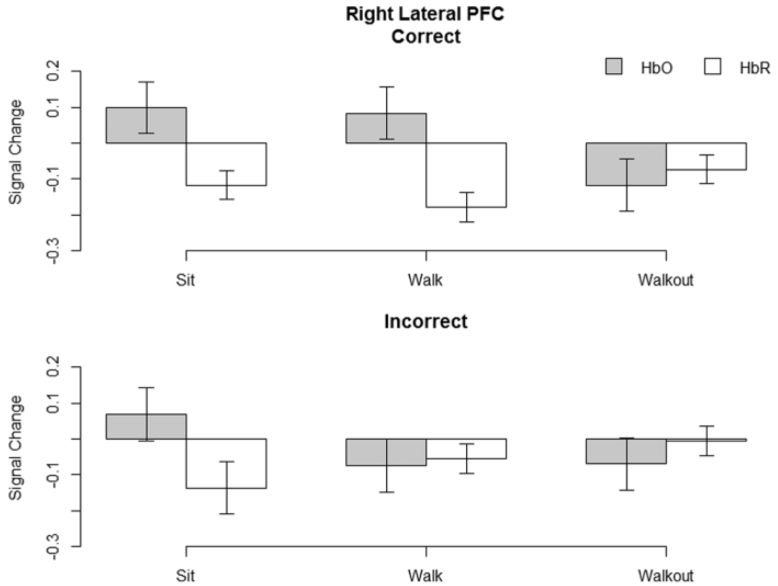

Figure 6. Right lateral prefrontal cortex (PFC) signal change in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) as a function of experimental condition and auditory 1-back block accuracy. Error bars represent standard errors of the beta coefficient estimate. Incorrect estimates for sit condition based on 19 trials and 2,280 functional near-infrared spectroscopy (fNIRS) samples; walk based on 17 trials and 2,040 fNIRS samples; walkout based on 22 trials and 2,640 fNIRS samples.

from Drexel University. Hasan Ayaz was involved in the technology development and thus was offered a minor share in fNIR Devices.

KEY POINTS

- Wireless functional near-infrared spectroscopy is capable of monitoring brain states in natural settings.
- In automatized physical tasks, physical work redistributes neural resources from prefrontal cortex when physical work and cognitive work compete.
- During physical and cognitive competition, environmental complexity reduces activity in bilateral prefrontal cortex from increased attentional load.
- Physical work and concomitant attentional load supersede executive processing in terms of mental resource distribution.

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Ryan McKendrick is an applied cognitive scientist at Northrop Grumman Aerospace Systems: Research Technology and Advanced Design. He received his PhD in human factors and applied cognition from George Mason University in 2016.

Ranjana Mehta is an assistant professor in the Department of Environmental and Occupational Health at Texas A&M University. She received her PhD in industrial and systems engineering from Virginia Tech in 2011.

Hasan Ayaz is an associate research professor at Drexel University, School of Biomedical Engineering, Science and Health Systems, Philadelphia, Pennsylvania. He is affiliated with the Department of Family and Community Health at the University of Pennsylvania as well as the Division of General Pediatrics at the Children's Hospital of Philadelphia. He received his PhD in biomedical engineering from Drexel University in 2010.

Melissa Scheldrup is a graduate research assistant in the Department of Psychology at George Mason University. She received her MA in human factors and applied cognition from George Mason University in 2014.

Raja Parasuraman was a university professor of psychology and director of the Center of Excellence in Neuroergonomics, Technology, and Cognition (CENTEC) at George Mason University. He obtained his PhD in applied psychology from Aston University in 1976.

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