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Neuroimaging of an attention demanding dual-task during dynamic postural control

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Abstract

Cognitive tasks impact postural control when performed concurrently as dual-tasks. This is presumed to result from capacity limitations in relevant brain regions. We used functional near-infrared spectroscopy (fNIRS) to measure brain activation of the left motor, temporal, and dorsal-lateral prefrontal brain regions of younger (n=6) and older (n=10) adults. Brain activation was measured during an auditory choice reaction task (CRT) and standing on a dynamic posturography platform, both as single-tasks and concurrently as dual-task. Body sway was assessed by median absolute deviation (MAD) of anterior-posterior translation of the center of mass (COM). Brain activation was measured as changes in oxy-hemoglobin by fNIRS. During both single- and dual-task conditions, we found that older adults had greater brain activation relative to younger adults. During dual task performance, the total activation was less than expected from the sum of individual conditions for both age groups, indicating a dual-task interference (reduction in younger adults=53% [p=0.02]; in older adults=53%; [p=0.008]). This reduction was greater for the

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activation attributable to the postural task (reduction younger adults=75% [$p=0.03$]; older adults=59% [$p=0.005$]) compared to the CRT task (reduction younger adults=10%, [$p=0.6$]; older adults=7.3%, [$p=0.5$]) in both age groups. Activation reduction was not accompanied by any significant changes in body sway in either group (older adults: single-task MAD=0.94 cm, dual-task MAD=1.10 cm, $p=0.20$; younger adults: single-task RMS =0.95 cm, dual-task MAD=1.08 cm, $p=0.14$). Our results indicate that neural resources devoted to postural control are reduced under dual-task conditions that engage attention.

Introduction

Postural control requires sensorimotor integration of vestibular, visual, proprioceptive, and tactile information. One theory proposes that this sensory information is continually utilized and reweighted by the brain to facilitate upright posture(1). In healthy individuals, the integration of this information in higher brain centers is mostly automatic (2). However, brain aging can reduce automaticity and increase the neural resources needed for postural control, contributing to risk for disability and falls(3, 4). Loss of automaticity becomes particularly apparent under dual-task conditions in which cognitive and postural tasks are completed concurrently, causing competition for neural resources. Dual-task impairments are more likely in older than younger adults due to loss of efficiency in attention networks(2). Therefore, older adults may require greater recruitment of neural resources in order to perform as well as younger adults under dual-task conditions. When cognitive or postural tasks are performed alone, a majority of neural resources can be devoted to that task allowing for optimal performance. When the two tasks are completed concurrently, as is more typical in real life situations, sufficient neural resources may not be present to perform both tasks optimally.

Age-related impairments in standing postural control are associated with declines in executive function and related centers in the brain(5–8). Executive functions decline with age(9) due in part to selective deterioration of the dorsolateral prefrontal cortex (dlPFC)(10). Dual-task studies of executive function and standing postural control have produced conflicting results, with some demonstrating dual-task interference and others not(2). Balance likely engages attentional processes to varying degrees, depending on task difficulty and the age and capabilities of the individual(5, 11). Difficult cognitive tasks may impair postural control by creating competition for resources(2). While previous standing postural dual-task studies have assessed behavioral performance, none have assessed the neural resources utilized. Understanding neural allocation of resources during dual-task can elucidate underlying mechanisms and may inform intervention approaches and improve risk assessment.

Functional near-infrared spectroscopy (fNIRS) is a non-invasive neuroimaging technique that can be used during balance and gait tasks(12–15). It uses low levels of light to record changes in oxy- and deoxy-hemoglobin in the brain. We used fNIRS to investigate neural activation in younger and older adults performing a cognitive auditory choice reaction time (CRT) task and a standing dynamic postural control task on a dynamic posturography platform. Participants completed each task separately as single-tasks and concurrently as

dual-task. fNIRS recorded brain activity from the left primary motor, pre-motor, temporal, and dlPFC brain regions. We hypothesized that older adults would have greater activation of these areas during dual-task compared to younger adults, because older adults have lower neural efficiency. We further hypothesized that activation observed during dual-task would be lower than expected from the simple sum of two single-task activations, indicating capacity limitations.

Methods

Subjects

Ten older (age range 66–81; seven female) and six younger (age range 22–30; two female) adults were screened for balance and neurologic abnormalities (see Supplemental Methods). Older adults were screened for cognitive impairment with the Repeatable Battery for Neuropsychological Status (RBANS)(16). Participant characteristics are in Supplemental Table 1. The University of Pittsburgh institutional review board approved all procedures and participants provided written informed consent.

Experimental design

Three tasks were completed: 1) postural control: single task of standing on a dynamic posturography platform, 2) attention: single task of an auditory choice reaction time (CRT) task while seated, and 3) dual-task: combined postural control and attention tasks. All trials were 121 seconds with 30 seconds of quiet sitting or standing at beginning and end to serve as baseline conditions. The fNIRS and balance response were measured relative to baseline conditions. Each condition was repeated three times with order randomized for each subject. Results of the three trials were averaged for all analyses.

Postural Control Task—Subjects stood with feet together and eyes closed on a dynamic posturography platform (NeuroTest, Neurocom International). A sway-referenced platform condition was used in which the platform rotated in the sagittal plane in proportion to the subject's body tilt(1). Body sway was measured by a magnetic tracking device (Fastrak, Polhemus) with a sensor on the lower back at the height of the iliac crest. The median absolute deviation (MAD) of the center of pressure translation of the low back sensor in the anterior/posterior direction was computed for postural sway. A harness prevented injury from falls but did not impede sway or give positional feedback.

Attention Task—An auditory CRT task presented participants with a 250ms 80dB sound pressure level tone at high (980 Hz) or low frequency (560 Hz). Participants responded with either a right- or left-hand button, depending on the frequency, which was randomly assigned before the trial. Presentation of stimuli occurred at random intervals with an inter-stimulus time between 2–6 seconds to reduce predictability. Response time in milliseconds (ms) was recorded.

fNIRS

A continuous wave fNIRS instrument (CW6 Real-time; TechEn Inc) and a 15 source-detector pair probe with eight 3.2cm channels were used (Figure 1). Each channel measured

wavelengths of 690nm (12mW) and 830nm (8mW) to measure both oxy- and deoxy-hemoglobin changes. The probe was anchored over the prefrontal, temporal, and motor cortices of the left hemisphere. Each trial was collected as a separate NIRS recording and synchronized to cue presentation. Optical sensor locations were marked relative to fiducial points then registered to the Colin27 MRI atlas(17) using a custom registration algorithm(18).

fNIRS Processing and Analysis

See Supplemental Methods for a detailed description. Briefly, the raw data were converted to changes in oxy- and deoxy-hemoglobin relative to the baseline condition using the modified Beer-Lambert relation. General linear models(19) based on an auto-regressively whitened and iteratively weighted robust regression algorithm were used. The model is of the form $Y = X*\beta$ where Y is a vector containing the fNIRS data for each measurement channel, X is the design matrix, and β is the vector of unknowns. The design matrix (X) models the expected response of the brain based on the timing of the task conditions and tests which fNIRS channels have hemoglobin changes that are statistically related to the change in the level of cerebral hemoglobin during the tasks compared to the baseline period. Here, the design matrix (X) contains four regressor types (Figure 2): single task CRT (β_1), single task postural control (β_2), and their dual-task equivalents (β_1' , β_2') where β_n denotes the coefficient in the regression model and is an entry in the vector β . We used a canonical general linear model(19) similar to the approach typical of functional magnetic resonance imaging (e.g. (20)). Statistical tests (T-test) are performed on linear combinations of these coefficients to test the null hypothesis that the coefficients are not different from zero.

In this study, we estimated the brain response to each component during dual-task (Figure 2). During dual-task, the brain response is modeled as a linear combination of the event-related response to the CRT (β_1') and the postural control task (β_2'). The dual-task interference effect was examined by comparing the amplitude of the brain response measured during the dual task condition ($\beta_1' + \beta_2'$) compared to the sum of the single-task responses ($\beta_1 + \beta_2$), which represents the theoretical response in the absence of interference. T-statistic tests were used to compare β values between single- and dual-task conditions. Similar to typical assumptions made in fMRI, this approach allows us to statistically address the null hypothesis that the single and dual-task responses were not different from each other under a first order (linearly additive) model, but does not rule out the additional possibility of higher order non-linear interactions.

Following first level statistical analysis, images were reconstructed based on the channel-space fNIRS data (Supplemental Methods). In brief, the probe location was registered to a template brain and Monte Carlo simulations estimated the sensitivity of the measurements to brain regions by an optical forward model(18). This model was inverted using a Bayesian restricted maximum likelihood model incorporating the subject-level data into a group mixed effects model.

A single region-of-interest (ROI) analysis was defined from a conjunction analysis across all stimulus conditions in both groups to find all channels activated ($p < 0.05$ based on oxy-hemoglobin) in one or more conditions. Responses were averaged over this ROI for each of

the conditions (β_1 , β_2) and estimated for each component of the dual-task condition (β_1' , β_2'). Dual-task costs were calculated as described above. Average responses for each ROI were compared between groups and conditions/components using one-way ANOVA.

Other Statistical Analyses

A paired T-test between single- and dual-task conditions was used to test differences in MAD, reaction time, and accuracy for both groups. An unpaired T-test was used to compare group-level differences within the single and dual-task trials. Reaction time was skewed, so we fit the distribution of correct responses to an exponentially-modified Gaussian distribution function(21) for each subject. The expectation of the centrality score (see Supplemental Table 2 for values and definitions) was used in statistical testing. The parameters of an exponential Gaussian distribution function were estimated using a non-linear (positively constrained) minimization.

Results

Individual reaction time, posturography, and fNIRS values are provided in Supplementary Tables 2–5.

Attention Task

During single-task CRT, older and younger participants had similar accuracy (older: 92.7% (SD=3.2%), younger: 89.0% (SD=4.0%); $p=0.06$) but older participants had significantly longer reaction times (older: 307ms (SD=40ms), younger: 228ms (SD=27ms); $p<0.001$). During dual-task, accuracy did not change for either group (older: 95.1% (SD=2.8%), comparison to single-task ($p=0.11$); and younger: 90.4% (SD=3.98%), $p=0.20$). Reaction times did increase during dual-task for older adults (332ms; SD=95ms; $p=0.01$) but only marginally increased for younger participants (243ms; SD=35ms; $p=0.05$).

fNIRS results indicated increased activation of the dlPFC to CRT for older adults during both single (β_1) and dual-task (β_1') conditions (Figure 3). In younger adults, increased activation in the dlPFC in response to the CRT stimulus occurred only in the single task condition, whereas the activation shifted to the supra-marginal (SMG) and superior-temporal (STG) areas during the dual task. Older participants showed a lower activation in the dlPFC during the dual-task compared to single-task (oxy-hemoglobin $p=0.02$; deoxy-hemoglobin $p=0.02$) whereas younger participants had a similar activation (oxy-hemoglobin $p=0.3$; deoxy-hemoglobin $p=0.2$) during both single and dual-task versions of the CRT task (Figure 3).

Postural Control

During single-task postural control, MAD was similar for both groups (older: 0.94cm (SD=0.25cm); younger: 0.95cm (SD=0.34cm); $p=0.9$). Activation reduction was not accompanied by any significant changes in body sway during dual task (MAD under dual-task, older: 1.10cm (SD=0.49cm); younger: 1.08 cm (SD=0.34cm); $p=0.14$).

The fNIRS measurements showed a typical hyperemic increase in oxy-hemoglobin and corresponding decrease in deoxy-hemoglobin which peaked approximately 10–15 seconds after the onset of the single-condition postural task (Figure 4). The response remained elevated for around 40–60 seconds after cessation of the task in the older group. This is considerably longer than expected based on the canonical hemodynamic response, which typically recovers in 12–15 seconds.

Spatially, brain activation during postural control was more widespread than the activation for CRT for the older adults, with increased activation in the dlPFC as well as SMG/STG (Figure 4). The brain response attributed to the postural component of the dual-task (β_2') was lower than in response to single-task postural control for the older participants (oxy-hemoglobin $p=0.03$; deoxy-hemoglobin $p=0.08$). The increased activation in the younger participants was more apparent in the SMG/STG for the single task, but there was almost no significant activation attributed to postural control during the dual-task. Thus the activation was greater for the single task compared with the dual-task (oxy-hemoglobin $p=0.03$; deoxy-hemoglobin $p=0.03$).

Dual-task Interference

The ROI included the left lateral frontal and superior temporal areas. Figure 5A shows the expected sum of brain activation from the two tasks performed separately ($\beta_1 + \beta_2$) alongside the observed response during dual-task ($\beta_1' + \beta_2'$) for each age group. For both groups, the observed dual-task response was lower than the expected sum of the two single-task responses (older: oxy-hemoglobin $p=0.02$; deoxy-hemoglobin $p=0.04$; younger: oxy-hemoglobin $p=0.008$; deoxy-hemoglobin $p=0.02$). Overall, the older participants had a larger response than the younger participants for both the dual-task response ($\beta_1' + \beta_2'$) (oxy-hemoglobin $p=0.006$; deoxy-hemoglobin $p=0.02$) and the sum of the single-task responses ($\beta_1 + \beta_2$) (oxy-hemoglobin $p=0.01$; deoxy-hemoglobin $p=0.02$).

Because of the larger response in the older participants, average brain responses were normalized to the mean of the single-task response for each group to demonstrate the proportional dual-task interference (Figure 5B). The brain response was significantly lower in dual-task ($\beta_1' + \beta_2'$) than the sum of single tasks ($\beta_1 + \beta_2$) (oxy-hemoglobin: older 53% lower, $p=0.02$, younger 53% lower, $p=0.008$; deoxy-hemoglobin: older 45% lower, $p=0.02$, younger 38% lower, $p=0.04$). The proportional change from single- to dual-task did not differ by age group (oxy-hemoglobin $p=0.6$; deoxy-hemoglobin $p=0.06$).

The brain response change between single- and dual-task conditions was larger for the postural task (older: oxy-hemoglobin 75% lower, $p=0.03$, deoxy-hemoglobin 58% lower, $p=0.08$; younger: oxy-hemoglobin 59% lower, $p=0.005$, deoxy-hemoglobin 57% lower, $p=0.03$) than for the CRT task (older: oxy-hemoglobin 10% lower, $p=0.6$, deoxy-hemoglobin 13% lower, $p=0.2$; younger: oxy-hemoglobin 7% lower, $p=0.5$, deoxy-hemoglobin 3% higher, $p=0.7$) for both age groups.

Discussion

During dual-task of attention and dynamic postural control, we found that older adults had greater activation of prefrontal and temporal regions compared to younger adults. These differential brain responses occurred despite similar performance on the tasks. Brain activation during the postural task was localized to the dlPFC and SMG/STG, whereas activation in response to the attention-demanding CRT task was specific to the dlPFC. Further, during dual-task, there were lower task-specific brain activations compared to the expected additive single-task response for both age groups. While the magnitude of this reduction was greater for older adults, the relative difference between expected and observed activation was similar for both older and younger participants. Finally, we observed greater reductions in the activation attributable to postural control from single- to dual-task conditions compared to activation attributable to CRT.

The dlPFC is believed to be involved in the coordination of concurrent and interfering task processing(22). Consistent with our results, studies using functional magnetic resonance imaging have shown that older adults have greater activation in the dlPFC when performing dual-task conditions in comparison to younger adults(23). The lateral frontal and superior temporal areas, which were activated during postural control, are associated with the secondary somatosensory network and activation has been observed in studies of balance and vestibular function(13–15, 24). Of note, the hemodynamic response that we observed during the postural task lasted longer than the typical canonical response. This is consistent with findings from other balance tasks in our lab(13–15), indicating that longer analytic windows, as used here, may be needed to assess fNIRS responses to these tasks. Furthermore, it may reflect the time needed for the sensory reweighting process, which can have an extended duration after environmental conditions change(1, 25). This experiment was not designed to fully examine the temporal dynamics of the brain responses and future studies are needed to understand this observation.

Processes active in postural control engage attentional resources and are subject to capacity limitations, although the extent of interference is likely determined by task difficulty and individual capabilities(2, 5, 7, 11). Attention becomes increasingly engaged as sensory conflicts arise in older adults(5) and may be particularly important in more complex postural control, such as in the presence of perturbations(26). We observed greater differences in activation between single and dual tasks in the estimation of the postural rather than the cognitive component. This may be due to the greater overall brain response to the postural control task; in the single-task condition, there may be more activation than needed to ensure sufficient postural control, allowing for a decrease during capacity limitations without impacts on postural performance. This is supported by a recent fNIRS study of dual-task walking demonstrating lower activation of the dlPFC in healthy older adults who maintained a faster gait speed during dual-task(27). Other studies have demonstrated a failure in appropriate task prioritization under cognitive load in older compared to younger adults(28). However, we observed a similar relative reduction in brain response to postural control in younger adults suggesting that this may not be an age-related maladaptive response. It is important to note that decreased activation related to postural control was associated with an increase in body sway for older and a decrease for younger adults during dual-task.

This study had several important limitations. First, while fNIRS allows neuroimaging while participants are upright, it is limited to the cortical surface. Further, our probe covered only left portions of the brain. Therefore, we are unable to comment on deeper structures or symmetry of responses. Second, because the fNIRS signal is restricted to the first few millimeters (around 5–8 mm) below the skull, greater atrophy in older compared to younger participants may have differential effects on signal strength. However, atrophy is most likely to result in less volume of brain tissue being included in the measurement and therefore, reduced signal strength. This would lead to underestimation of signal differences between older and younger participants. In addition, our groups were not balanced on gender, which may have confounded the results.

Several strengths should be noted. This is the first study to utilize fNIRS during a dynamic postural control dual-task, allowing for assessment of brain responses in relation to task performance. Second, we utilized the differing time courses of the tasks to disassociate the brain response attributable to each component. This allowed us to test differential effects of capacity limitations on the attentional and postural components of the dual-task.

Our results indicate that the neural resources devoted to postural control are reduced under dual-task conditions that engage attention. This resulted in a marginal increase in body sway in the older adults during dual-task. Falls are common and costly in older adults and are more prevalent in those with poor attention(29). Understanding the neural contributions to reduced postural control in older ages, particularly under dual-task conditions, could lead to novel intervention strategies and improved risk assessment. Although this current study was limited to a small sample size and focused only on brain recordings from the left hemisphere, we believe this work demonstrates the feasibility of using fNIRS brain imaging to look at allocation of cognitive resources during upright balance tasks and dual-task performance and is an important first step in designing future studies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

Older age was associated with greater brain activation for all conditions.

Dual-task conditions showed a reduction in activation compared to single-task.

Older subjects had a greater dual-task interference compared to younger subjects.

The dual-task reduction was greater for the postural component of the task.

fNIRS can elucidate the neural mechanisms behind dual-task costs.

Figure 1. Functional NIRS setup

A portable functional near-infrared instrument (panel A) was used to record brain signals from participants using a head cap worn during standing (panel B). The fNIRS cap consisted of 4 source and 8 detector positions arranged with a 3.2cm separation distance as shown in panels C and D.

Single-Task Response

Figure 2. Schematic of the fNIRS general linear model and calculation of dual-task interference
 The functional near-infrared spectroscopy response is modeled using a linear regression model with four coefficients of interest (β) modeling the single-task and dual-task responses to the choice reaction task (CRT) and postural task. From these four terms, the dual-task capacity [$\beta_1' + \beta_2'$] and dual-task cost [$(\beta_1 + \beta_2) - (\beta_1' + \beta_2')$] can be estimated.

Figure 3. Attention Task Brain Response

The reconstructed functional near-infrared spectroscopy brain responses to the choice reaction task (CRT) are shown above during the single and dual-task conditions. In panel A, the CRT response during the single-task condition is shown for both subject groups. In panel B, the CRT component of the dual-task response is shown.

Figure 4. Postural Control Brain Response

The functional near-infrared spectroscopy brain responses to the single-condition postural control task for the older (top row) and younger (bottom row) groups are shown above. In panel A, the CRT response during the single-task condition is shown and in panel B, the CRT component of the dual-task response is shown.

Figure 5. Region-of-interest analysis of brain responses

A. The oxy-hemoglobin brain responses for the choice reaction time (CRT) and postural control tasks are shown for the single- and dual-task trials based on region-of-interest averages from the conjunction ($p < 0.05$) of all trial types across both groups. The sum of the individual magnitudes of the single-task responses are shown in a single bar ($\beta_1 + \beta_2$) to demonstrate the expected dual-task response in the absence of interference. This is in contrast to the observed dual-task response ($\beta_1' + \beta_2'$). B. The same results are presented normalized to the average single-task response for each group (e.g. $\beta_j / \langle \beta_i \rangle$ where $\langle \beta_i \rangle$ denotes the average of the single-task response). Here, the percent reduction of the response between the single- and dual-task versions is demonstrated. The error-bars provide the standard errors estimated from the group-level mixed effects model and region-of-interest averages. Additional information about the individual subject results is given in the supplemental material. “ η ” denotes normalization to the single-task conditions.