EEG measures reveal dual-task interference in postural performance in young adults

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Abstract The study used a dual-task (DT) postural paradigm (two tasks performed at once) that included electroencephalography (EEG) to examine cortical interference when a visual working memory (VWM) task was paired with a postural task. The change detection task was used, as it requires storage of information without updating or manipulation and predicts VWM capacity. Ground reaction forces (GRFs) (horizontal and vertical), EMG, and EEG elements, time locked to support surface perturbations, were used to infer the active neural processes underlying the automatic control of balance in 14 young adults. A significant reduction was seen between single task (ST) and DT conditions in VWM capacity ($F(1,13) = 6.175$, $p < 0.05$, $r = .06$) and event-related potential (ERP) N1 component amplitude over the L motor ($p < 0.001$) and R sensory ($p < 0.05$) cortical areas. In addition, a significant increase in the COP trajectory peak (pkcpx) was seen in the DT versus ST condition. Modulation of VWM capacity as well as ERP amplitude and pkcpx in DT conditions provided evidence of an interference pattern, suggesting that the two modalities shared a similar set of attentional resources. The results provide direct evidence of the competition for central processing attentional resources between the two modalities, through the reduction in amplitude of the ERP evoked by the postural perturbation.

Keywords Balance · Posture · Event-related-potential · Dual task · Cortical activity · Electroencephalography

Introduction

Research supports the systems model of postural control, which maintains that multiple sensory systems contribute to the control of posture, including vestibular, visual, and somatosensory systems (Macpherson and Inglis 1993; Horak et al. 1988; Horak and Nashner 1986). Research suggests that cerebral cortex and high-level cognitive processing also contribute to aspects of balance control, as postural and/or cognitive performance has been altered in some dual-task (DT) (performing two tasks at once) contexts (Lajoie et al. 1993; Woollacott and Vander Velde 2008). Interference is thought to occur when two attentionally demanding tasks compete for a set of limited attentional processing resources. It has been posited that if two tasks performed simultaneously require more than the total attentional capacity, the performance of one or both tasks will be affected negatively (Wickens 1983). Thus, interference between cognitive processing and balance function was thought to indicate cortical involvement in the maintenance of postural equilibrium.

Reactive responses are essential to recover stability in conditions when stance balance is threatened. When the onset or magnitude of instability is unpredictable such as tripping or sudden stops and starts on a subway, train, or bus, the automatic postural recovery responses are influenced by the stimulus and generated at short latencies (<200 ms) (Nashner 1977; Nashner and Cordo 1981; Runge et al. 1999). These automatic or reactive postural responses are typically characterized by ground reaction force (GRF) vectors in both the anterior–posterior (A–P) and the vertical planes (A–P force and motion of the center of pressure (COP) trajectory), movements of body segments, electromyography (EMG) of postural muscles and electroencephalographic (EEG) activity (Horak and Nashner 1986; Horak

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et al. 1989; Quant et al. 2005; Mochizuki et al. 2009). By evaluating the combined outcomes of these postural measures, researchers have been able to infer the active neural processes underlying balance control.

Common EEG event-related potential (ERP) components have been identified in the area of cognitive neuroscience and include P1, N1, P2, N2, and P3; such labels refer to the polarity (N being negative and P positive) and position of the element within the waveform (Luck 2005). The presence or absence of these components varies across modalities as well as scalp site; thus, sensory components from different modalities that are given the same labels are not linked in any way to function of the underlying brain activity, e.g., the auditory P1 and N1 bear no particular relationship to the visual P1 and N1 (Luck 2005; Hillyard et al. 1998). The components typically observed in ERPs time locked to support surface perturbations include P1, N1, and P2. However, as stated earlier, their presence has varied across postural studies (Quant et al. 2004, 2005; Adkin et al. 2006, 2008; Dietz et al. 1985). The ERP peak latency also varies to some degree across modalities; e.g., onsets time locked to support surface perturbations have been sited as follows, P1 (40–45 ms), N1 (100–160 ms), and P2 (250–300 ms) (Dietz et al. 1985; Quant et al. 2004, 2005; Mochizuki et al. 2009).

Many DT postural studies have quantified interference patterns by highlighting variations in the timing and magnitude of postural measures in ST versus DT conditions (Siu et al. 2008; Maki et al. 2001; McIlroy et al. 1999). Fewer DT studies have attempted to characterize the role of the cerebral cortex during postural recovery using ERPs, time locked to postural perturbation (Quant et al. 2004, 2005; Adkin et al. 2006). One such study that paired a visual-manual tracking task with support surface perturbations showed altered performance in both tasks and attenuation in N1 (Quant et al. 2004). Research suggests that N1 is associated with sensory processing of information related to the perturbation (Dietz et al. 1984; Quant et al. 2005). The secondary task may have reduced aspects of sensory processing related to postural recovery. Not all of the postural DT research has shown interference between postural (automatic recovery response) and cognitive task performance (Dault et al. 2001; Norrie et al. 2002). This may be due (1) to different levels of difficulty used for one or both tasks and/or (2) to the nature of the cognitive resource targeted during the tasks (Logie et al. 1990; Cocchini et al. 2002).

Working memory (WM) tasks have routinely been used in DT postural paradigms to evaluate interference patterns between modalities. However, many WM tasks involve both information storage and processing, with the majority requiring the preservation of information while concurrently processing the same or other information (e.g., reading span tasks, counting span tasks, verbal response to auditory

stimuli, the N-back task, or the Brooks (1984) spatial memory task (Lajoie et al. 1993; Huxhold et al. 2006) McCollough et al. (2007) showed that the change detection task used only temporary retention (storage) of visual information with no updating or manipulation. Results from studies that have used this task to probe VWM capacity converge, suggesting a fixed limited capacity (defined as the number of unique items held in WM, 3–4 in young adults (YAs) (Vogel and Machizawa 2004; Pashler 1988). Studies using functional magnetic resonance imaging (fMRI) and lateralized electrophysiological techniques have identified regions in the posterior parietal and occipital cortex whose activation levels during a VWM task were tightly correlated with behavioral measures of VWM capacity (Vogel and Machizawa 2004; McCollough et al. 2007; Xu and Chun 2006). Thus, the change detection task was selected to help provide further insight into cortical interference patterns when a postural task was combined with a VWM task.

Our aim was to analyze ERP components to determine whether postural response characteristics would be affected in the DT versus ST postural conditions. We posited that pairing of a VWM task that used only temporary retention (storage) of visual information with no updating or manipulation (targeted a single cortical region) with a challenging postural task (perturbation of the support surface) would require more than the total available attentional capacity. We predicted that performance in one or both tasks would be altered. We hypothesized that there would be a decline in VWM capacity in ST versus DT conditions as well as an increase in EMG and GRF measures with respect to the automatic postural response (as shown previously by Quant et al. 2004). A change in performance of both modalities would reflect the sharing of attentional resources as opposed to a shift in resources from one modality to another. It was proposed that if cognitive and postural modalities were in competition for a limited set of attentional resources, that we would see attenuation in ERP magnitudes between ST and DT conditions particularly in the N1 component of the ERP, as its peak latency (100–160 ms) is in the short latency range (60–200 ms) associated with the automatic postural recovery response. We hypothesized that there would be no change in latency in ERP components (P1, N1, and P2) in ST versus DT conditions.

Materials and methods

Participants

This study is part of a larger project that used a similar DT experimental paradigm. An interference pattern was observed between VWM capacity and the automatic

postural recovery response following posterior support surface perturbation in session 1 of the project (Little and Woollacott 2014). The change detection task had not been used in a DT paradigm up to this point. In the initial study, data collection and analysis included VWM capacity and postural measures such as GRFs (vertical and horizontal), kinematics, and EMG magnitudes with no EEG.

A subset from the original 34 YAs returned to participate in session 2 of the study: 14 YAs (11 females and 3 males). Subjects ranged in age from 19 to 24 years (mean age, height, and mass: 20.6 ± 1.5 , 170.8 ± 9.5 cm, and 70.2 ± 11.4 kg, respectively). YAs were included with no history of concussion or mild traumatic brain injury (mTBI) and were excluded if taking medication known to affect postural control or cognitive function. Participants were informed of experimental conditions and gave written consent prior to initiating the testing sessions. All procedures were approved by the office for protection of human subjects at the University of Oregon.

Protocol

Cognitive task

The change detection task was used to predict VWM capacity. During the initial consolidation/encoding phase, memory arrays of 2, 4, or 6 squares were viewed for 500 ms, followed by a blank gray screen with a central cross (distance of 70 cm), during which subjects retained in memory the number, position, and color of the array for 900 ms. Directly following, during the 2,000-ms retrieval phase, a test array was presented and subjects indicated whether memory and test arrays were identical or different using bilateral button presses (Left—no change and Right—change). Square color was the only feature of the array that was changed between presentation of the memory and test arrays.

Each set of squares was presented 30 times for a total of 90 trials. All subjects were familiarized with the task during an initial training session, and this thus eliminated a learning effect during data collection. An algorithm was developed to randomly select from a set of seven highly discernable colors (red, blue, violet, green, yellow, black and white); individual colors appeared no more than twice within an array. Stimulus positions were randomized on each trial, with the constraint that the distance between squares was at least 2° (center to center). The color of one square was different in half of the test arrays. An adjustable tripod with a platform was used to raise and lower the screen between postural conditions.

Postural conditions

Postural conditions included backward perturbation of the support surface (1) with no VWM task (ST condition)

and (2) while performing the VWM task (DT condition). To eliminate habituation of perturbation onset the time between perturbations was randomized, with times between 8 and 15 s, memory arrays of 2, 4, or 6 squares (change detection task trials) were randomly presented (ranging from 10 to 20 trials), between perturbation trials to prevent subjects from predicting when the perturbation would occur (referred to as “intermittent” trials). Forward perturbations were included to reduce the tendency of subjects to prepare for a perturbation by leaning backwards in order to reduce forward sway; it thus promoted upright positions of stance between perturbations of the support surface. These forward direction perturbations were interspersed among trials in both ST and DT conditions and were not included in the statistical analysis. VWM capacity obtained during sitting from session 1 was the control condition used for comparison for each subject who returned in session 2. Although results from work by Lajoie et al. (1993) suggested that standing used greater cortical resources than sitting, no significant difference in VWM capacity was seen in YAs when sitting (control) and stance (no perturbation) conditions were compared in session 1 (Little and Woollacott 2014). A significant difference was seen between sitting (control) and perturbation conditions in the previous study; thus, we posit that the difference between stance (no perturbation) and perturbation would also have been significant. Since sitting is the control condition when the VWM task is used as part of a cognitive neuroscience protocol, it was chosen as the control condition for session 2 comparisons.

Subjects selected a comfortable stance position that was traced on the force plates using masking tape and asked to maintain neutral posture; if subjects took a step, they were instructed to resume the initial traced position. They were instructed to focus equal attention on the postural task and the VWM task in the DT condition. Platform movement occurred immediately following presentation of the 500 ms memory array in the DT condition, coinciding with the beginning of the retention interval. Fourteen ST perturbation trials preceded and 11 followed the 90 DT trials. Table 1 summarizes the change detection task used within the experimental paradigm. To ensure visual demands remained constant between conditions, a cross was projected on the monitor during ST conditions and subjects were asked to focus on the cross. Subjects were instructed to randomly depress the buttons they held in their hands during the ST condition, to keep any additional motor requirements constant across both tasks. Subjects wore a safety harness attached to an overhead trolley to ensure safety during the perturbations in case a loss of balance occurred.

Table 1 Summary of cognitive task experimental protocol and identification of trials used to estimate VWM capacity (K)

Summary of experimental paradigm and trials used in data analysis			
Postural condition	Single task (ST)	Dual task (DT)	Analysis
Control: sit	Change detection task (set size 2, 4, and 6 squares)	2 squares* 30 trials (trls) 4 squares* 30 trls 6 squares* 30 trls	NA
Perturbation	No change detection task	ST = trls 1–14 and 117–127 Change detection task (set sizes 2, 4, and 6 squares)	Correct and incorrect responses from 90 trials were collated. VWM capacity (K) was calculated for each subject. (See formula in text) NA NA 30 pert. trials of SS 2 squares 30 pert. trials of SS 4 squares 30 pert. trials of SS 6 squares ST = trls 1–14 DT = trls 15–116 (ST = 1 forward trl and DT = 11 forward trls removed) K was estimated for each subject using the set size responses from the 90 DT perturbation trials

Data collection

EEG data collection

Continuous EEG was recorded using the HydroCel Geodesic Sensor net with 256 channels developed by Electrical Geodesics, Inc.; conduction of cortical activity occurred through electrodes surrounded by sponges soaked in an electrolyte (Fig. 1a). A central electrode was the reference for the remaining 255 channels. Impedance threshold was maintained at or below 50 Kilohms throughout data collection; cortical data were amplified (X2000), notch filtered at 60 Hz to remove noise from the lights in the room, and sampled at 1,000 Hz using a Net Amps 300 amplifier. The software package NetStation, developed by Electrical Geodesics, Inc., was used to analyze the EEG.

EMG data collection

Electromyography (EMG) was sampled at 1000 Hz using a Motion Analysis Acquisition Unit (12 bit A/D inputs with a ± 5 V range and amplifier with a gain of 10—resolution 2.441 mV/bit). Raw EMG was amplified through a pre-amplifier, DC Power Supply ± 5 V at 2.5 mA, with an input impedance greater than 100 M Ω using pairs of bipolar surface electrodes (disposable blue sensor, silver–silver chloride, Medicotest, Inc.) with an inter-electrode distance of 2 cm. The following muscles were recorded bilaterally: tibialis anterior (TA), gastrocnemius (GA), rectus femoris (RF), hamstrings (HA), and erector spinae (ES) at lumbar_{4–5}.

Force plate

Support surface perturbations were applied using a servo-controlled, hydraulically driven platform system built by the Institute of Neuroscience Technology Group at the University of Oregon. Two force plates moved in unison; the input waveform was a ramp to parabola with a displacement amplitude of 10 cm, peak velocity of 30 cm/s of 0.5 s duration, and acceleration of 0.34 m/s/s.

Data analysis

VWM capacity

A simple equation was used to estimate the number of items (K), maintained in WM (Pashler 1988). K was determined using the following formula, $K = SS (HR + CR - 1)$, where SS = set size (2, 4, and 6), HR = hit rate (number of times the change in squares was correctly identified), CR = correct rejection (number of times no change in squares was correctly identified). WM capacity (K) was

Fig. 1 **a** YA wearing Hydro-Cel Geodesic Sensor net (256 channels) gazes at the screen, depressing buttons randomly during the ST condition and responding to change detection task trials in the DT condition. **b** Four of many possible square configurations

a Experimental Paradigm.

b Four different possible square configurations.

calculated for each set size (30 trials) and used to calculate the average for the 90 trials by summing K for each set size and dividing the total by the number of set sizes included in the VWM task, 3. The estimate of K was based on the presentation of 90 change detection trials during the control (sitting) and perturbation (trials 15–116) conditions. Figure 1b presents 4 possible examples of set size configurations.

ERP data reduction

Event-related potentials, time locked to the support surface perturbation, were analyzed using the Net Station software package. Data were high-pass then low-pass filtered at cutoff frequencies of 0.1 and 30 Hz, respectively. Data were segmented including 700 ms before and 900 ms after perturbation onset. An artifact detection algorithm and visual inspection were applied, and those segments with artifacts were removed from the analysis; 1 subject stepped during 1 trial in the ST condition and 3 stepped in the DT condition (2 subjects in 1 trial and a third in 4 trials). The analysis included 3 segment windows that corresponded with P1 (20–120 ms), N1 (50–190 ms), and P2 (130–260 ms) components of the ERP following perturbation (0 time point) and was selected based on the grand-averaged baseline corrected file. The averaged data were visually inspected to ensure ERP components were located within the respective time windows for each subject. Electrodes over 4 areas of the cortex were chosen; a montage of 4 electrodes in close proximity to each other

was selected to ensure similar waveforms, to characterize the cortical response for the two postural conditions (ST and DT).

Event-related potential amplitudes and onset latencies were evaluated for the 3 components (P1, N1, and P2) with the focus being on N1 as it characterized cortical activation associated with the automatic postural response (Fig. 2). Trials 1–14 represented ST and trials 15–116 represented DT performance. The focus of the analyses was on averages from electrodes over 4 areas of the cortex, Right (R) Primary (P) Motor (channels 185, 186, 198, and 197), Left (L) P Motor (channels 9, 17, 43, and 44), R Sensory (channels 81, 131, 132, and 144), and L Sensory (channels 45, 53, 80, and 79).

Net Station describes ERP amplitude as the adaptive mean determined by an algorithm that finds a peak within the ERP event window and then defines a new time window around this peak. The polarity convention used is as follows: negative is up and positive is down; thus, in the case of N1, the algorithm reports the mean centered with respect to the negative peak for a window of 10 ms in either direction of the peak (10 ms before and after the peak). The amplitude (μV ms) is calculated from the new 20 ms time window under the ERP trajectory. The amplitude is reported as the average of the four electrodes in the channel group for each cortical area (4 were included). An algorithm was used to determine the time to ERP peak (ms) referenced to perturbation of the support surface. Table 2 presents the means from the 4 regions over the cortex (signals from 4 electrodes collated).

Young Adults: Grand Average ERPs

a Right Motor - Channel 198 **b** Left Motor - Channel 9 **c** Right Sensory - Channel 81 **d** Left Sensory - Channel 79

Fig. 2 Example of grand average ERPs comparing ST and DT conditions for 14 YAs from electrodes positioned over: **a** R motor cortex (channel 198), **b** L motor cortex (channel 9), **c** R Sensory cortex (channel 81) and **d** L Sensory cortex (channel 79)

EMG data reduction

Means from trials 10–14 (ST) were compared to trials 15–19 (DT). If steps were taken during any of the trials typically included in the ST or DT trial sets, alternative trials directly preceding or following were used, to include 5 trials per trial set. Trials in which steps were taken were also not included in the overall analysis of postural variables (the mean number of trials in which a step was taken: ST = 0.07 ± 0.27 ; DT = 0.43 ± 1.1); distinctly different force and neuromuscular response strategies are used for taking steps versus using an in place strategy to recover balance. The postural data were subdivided in this manner to separate the DT effect between ST and DT conditions from any attenuation of postural responses, which could occur following repeated application of the same stimulus (Horak and Nashner 1986; Macpherson et al. 1989).

The EMG data were high-pass filtered (cutoff frequency of 10 Hz) and then full-wave rectified and low-pass filtered (cutoff frequency of 35 Hz). Right and L muscle EMG traces were averaged. Magnitudes were quantified by area under the EMG curve (mV ms) for 2 bins of 80 ms width (90–170 and 170–250 ms). The 2 time bins captured events occurring during the early (bin 1) versus late (bin 2) phase of the automatic

postural response (Horak et al. 1989). An algorithm was used to determine EMG onset latencies with the following criteria: 3 SD above baseline activity (200 ms preceding perturbation) sustained for 50 ms and visual inspection.

Force data reduction

Vertical GRFs were combined bilaterally to characterize the trajectory of the COP along the anterior–posterior (A–P) axis. The COP data were low-pass filtered at a cutoff frequency of 50 Hz and re-sampled at 100 Hz. The area under the COP trajectory along the A–P axis was quantified in mm ms for two consecutive bin widths of 80 ms (190–270 and 270–350 ms following onset of platform movement) plus 100 ms of estimated excitation–contraction coupling time. The COP peak (cm) following support surface perturbations was determined and included in the analysis. Area under the A–P force trajectory, in N-ms, was also quantified for the same 2 bins. In addition, the difference in A–P force from the beginning to the end of the bin was also included in the analysis.

Statistical analysis

To facilitate across-subject comparisons, EMG amplitudes were normalized to the absolute value of the mean

Table 2 Mean amplitude and time to ERP peak for the waveform elements of N1, P1, and P2 over 4 regions of the cortex in YAs

Cortical measure	Cortical region	Single task	Dual task
N1 amplitude (μ V ms)	R motor	-24.4 ± 10.4	-21.2 ± 11.7
	L motor	-26.0 ± 11.2	-20.2 ± 8.7
	R sensory	-28.9 ± 9.5	-24.0 ± 7.7
	L sensory	-24.4 ± 11.4	-20.5 ± 8.5
Time to N1 ERP peak (ms)	R motor	117 ± 13	112 ± 26
	L motor	119 ± 10	110 ± 16
	R sensory	118 ± 16	110 ± 18
	L sensory	114 ± 15	106 ± 16
P1 amplitude (μ V ms)	R motor	3.5 ± 2.5	3.0 ± 4.2
	L motor	3.0 ± 4.2	2.8 ± 3.0
	R sensory	5.1 ± 3.4	2.7 ± 1.2
	L sensory	5.0 ± 3.7	2.7 ± 2.7
Time to P1 ERP peak (ms)	R motor	54 ± 22	46 ± 22
	L Motor	51 ± 18	41 ± 23
	R sensory	49 ± 17	45 ± 16
	L sensory	47 ± 17	42 ± 21
P2 amplitude (μ V ms)	R motor	7.3 ± 10.4	6.4 ± 11.0
	L motor	6.8 ± 16.3	7.2 ± 8.7
	R sensory	6.6 ± 9.4	7.6 ± 9.7
	L sensory	4.9 ± 7.1	5.8 ± 6.7
Time to P2 ERP peak (ms)	R motor	198 ± 32	199 ± 36
	L motor	199 ± 36	188 ± 23
	R sensory	214 ± 30	218 ± 34
	L sensory	207 ± 24	203 ± 38

from the 5 ST trials preceding the DT trials relative to bin 1 for all trials; including TA-bin1 and 2, GA-bin1 and 2, RF-bin1 and 2, HA-bin1 and 2, and ES-bin1 and 2. The dependent variable associated with behavioral cognitive performance included VWM capacity (K). The dependent postural variables included characteristics of the ERPs (P1, N1, P2 amplitudes, time to P1, N1, P2 peak and N1 onset latency), area under the A–P force trajectory (Fap), change in A–P force between the beginning of the bin and the end of the bin (FapDiff), the COP trajectory peak (pkcpx), area under the COP trajectory (Acopx), normalized EMG amplitudes (nGA, nHA, nES, nTA, and nRF) for both bin 1 and bin 2, and EMG onset latencies.

The statistical package SPSS was used for analysis (Field 2009). The study was a repeated-measures design. Significance level was set to p values less than $p = 0.05$. An effect size of 0.1 was considered small, 0.3 moderate, and 0.5 large (Field 2009). One-way repeated-measures analysis of variance (ANOVA) was used to analyze the effect of postural condition (ST vs. DT) on VWM capacity (K). Separate two-way repeated-measures ANOVAs were used to analyze the effects of condition (ST vs. DT) on P1, N1, and P2 ERP components (amplitude and time to peak). Post

hoc Bonferroni corrections analyses were used after the first stage of the analysis, dependent upon the significant interactions or main effects that were revealed. N1 time to ERP peak latencies (ms) were compared between motor and sensory areas using Bonferroni correction. The effect of condition (ST vs. DT) on EMG amplitude and onset latency was determined using two-way repeated-measures ANOVAs. Post hoc Bonferroni corrections analysis was used to identify specific onset differences across muscle groups. Two-way repeated-measures ANOVA evaluated the effect of condition (ST vs. DT) on postural measures that included pkcpx, Acopx, Fap, and FapDiff. Repeated contrasts were specified a priori with respect to the postural measures and reported when the first stage of the analysis revealed a significant interaction.

Results

VWM capacity—K

Evaluation of the effect of increased postural demand on VWM capacity demonstrated a significant main effect of postural condition, $F(1,13) = 6.175$, $p < 0.05$, $r = 0.6$. There was a significant reduction in VWM capacity between the control (sit) and the perturbation condition.

ERP measures

When data were compared across subjects, perturbations in the backward direction, causing forward sway, evoked large N1 with small P1 and P2 components of the ERP time locked to support surface perturbations. Four electrode sites were analyzed in each region, and Fig. 2 provides examples of ERPs from individual channels over 4 cortical areas. A significant interaction was observed between condition (ST vs. DT) and EEG amplitude with P1, N1, and P2 included in the analysis, $F(3, 11) = 22.668$, $p < 0.05$, $r = 0.8$. Postural condition appears to have had an influence on the cortical response. Post hoc Bonferroni corrections revealed a significant decrease in mean N1 amplitude in DT compared with ST conditions in the following cortical areas; L P Motor ($p < 0.001$), R Sensory ($p < 0.05$) but not the R P Motor ($p < 1.000$) and L Sensory ($p < 0.921$) (see Table 2). Further, post hoc Bonferroni corrections showed no significant change in amplitude between ST and DT conditions for P1, R P Motor ($p < 1.000$), L P Motor ($p < 1.000$), R Sensory ($p < 0.458$), and L Sensory ($p < 0.441$) or for P2, R P Motor ($p < 1.000$), L P Motor ($p < 1.000$), R Sensory ($p < 1.000$), or L Sensory ($p < 1.000$). No significant interaction was observed between postural condition (ST vs. DT) and time to peak for any of the ERP components, $F(3,11) = 0.849$, $p < 0.638$. Table 2 outlines the mean

amplitude and time to ERP peak for P1, N1, and P2 in both ST and DT conditions for all 4 cortical regions.

As N1 was the only ERP component to show a significant reduction in amplitude during the DT condition, N1 time to ERP peak latencies (ms) were compared between Motor and Sensory areas. Post hoc Bonferroni analysis showed no significant difference between ST or DT conditions; ST: R Primary Motor (117 ± 13) versus R Sensory (118 ± 16), $p < 1.000$ and L Primary Motor (119 ± 10) versus L Sensory (114 ± 15), $p < 1.000$, DT: R Primary Motor (112 ± 26) versus R Sensory (110 ± 18), $p < 1.000$ and L Primary Motor (110 ± 16) versus L Sensory (106 ± 16), $p < 1.000$. Since afferent information is thought to arrive first in the sensory cortex and then relayed on to the motor cortex, we expected to see ERPs associated with the sensory cortex with earlier peak latencies than those in the motor cortex.

Figure 2a and b present grand average ERP components that compare ST and DT conditions for 14 YAs from electrodes positioned over the R P Motor cortex (channel 198) and L P Motor cortex (channel 9), respectively, and Fig. 2c and d over the R Sensory cortex (channel 81) and L Sensory cortex (channel 79), respectively. The amplitude of the N1 ERP component was attenuated in each of the examples presented.

EMG measures

Postural condition (ST vs. DT) appeared to have no effect on muscle magnitude with no significant interaction effect seen between condition and muscle group, $F(7,71) = 1.680$, $p < 0.110$. No interaction was seen between postural condition (ST vs. DT) and EMG onset latency, $F(4,35) = 0.655$, $p < 0.627$. Thus, no DT effect was seen for either EMG magnitude or latency. However, a significant main effect of muscle was identified, $F(4,35) = 96.958$, $p < 0.001$, $r = 0.86$. Since EMG onset latencies did not differ between postural conditions, ST and DT latencies were combined and the temporal sequence of muscle activation evaluated. Mean onset latency for each muscle group included: TA: 112 ± 20 ms, GA: 86 ± 10 ms, RF: 103 ± 31 ms, HA: 126 ± 29 ms, ES: 154 ± 37 ms. Bonferroni corrections analysis identified specific onset differences across muscle groups, TA versus GA ($p < 0.001$), GA versus RF ($p < 0.001$), RF versus HA ($p < 0.001$), and HA versus ES ($p < 0.001$). However, no significant difference was seen between onset latencies for RF versus TA ($p < 0.123$). Thus, a distal to proximal temporal sequence of muscle activation was seen on the dorsal surface of the body with co-contraction of RF and TA on the ventral surface. EMG data were not collected from the abdominal muscles in the current study.

Postural measures

A significant interaction effect of condition (ST versus DT) by postural measure was identified, $F(7,73) = 2.336$, $p < 0.05$, $r = 0.2$), which suggests that condition influenced postural response. A priori repeated contrasts revealed a significant increase in the COP trajectory peak (pkcpx) for the DT compared with the ST condition, $F(1,79) = 5.655$, $p < 0.05$, $r = 0.3$. However, no significant difference was seen for Acopx-bin1 ($F(1,79) = 0.004$, $p < 0.952$), Acopx-bin2 ($F(1,79) = 1.148$, $p < 0.287$), Fap-bin1 ($F(1,79) = 0.589$, $p < 0.445$), Fap-bin2, $F(1,79) = 0.601$, $p < 0.440$, FapDiff-bin1, $F(1,79) = 0.551$, $p > 0.460$, and FapDiff-bin2, $F(1,79) = 2.049$, $p < 0.156$).

Discussion

The main aim of the study was to determine the way in which a visual-spatial cognitive task affected the cortical activity induced by a postural perturbation. We hypothesized that the DT context would reduce the efficiency of both the visual-spatial task performance (reduced VWM capacity) and recovery from the postural threat (increased A-P COP displacement). We also hypothesized that the N1 ERP evoked by the perturbation would be attenuated, but that the peak latency would not be affected, based on the previous research results (Quant et al. 2004).

Performance was significantly affected in both the postural and cognitive tasks. VWM capacity decreased between ST and DT conditions. In isolation, this result could suggest a re-allocation in resources from the cognitive to the postural task. However, evaluation of measures associated with the postural response showed a significant increase in the COP trajectory peak (pkcpx) in the DT condition, which could reflect a less efficient postural response. This would thus suggest that competition for attentional resources under DT conditions was associated with a reduction in both cognitive and postural task performance. A similar effect was seen, in the DT postural study by Quant et al. (2004), using stance perturbations.

As hypothesized, the amplitude of the N1 ERP component was attenuated in the DT versus ST condition. Since the N1 peak in this paradigm has been associated with the processing of sensory inputs for postural control, this supports the theory that competition between the two tasks diverted attentional resources from the processing of sensory inputs associated with the postural perturbation (see Dietz et al. 1984; Quant et al. 2004). Similarly, a study by Quant et al. (2004) showed that the N1 ERP component associated with postural perturbations was reduced when subjects performed a visual-manual tracking task continuously during the perturbations.

The exact nature of cortical involvement with respect to the automatic postural response is unclear. Dietz et al. (1985) have argued that since the onset latency of afferent, perturbation-related ERPs are only slightly and nonsignificantly shorter than that of the muscle response (e.g., in our study, ST-N1 onset latency was 82 ± 7 ms, time to N1 peak was 117 ± 13 ms, and EMG (GA) was 86 ± 10 ms) that the ERP is probably not part of a trans-cortical loop. We postulate that the ERP may be associated with afferent information used by the CNS in modifying “central postural set.” The “central postural set” relates to the influence of the central drive on automatic postural responses to external perturbations (Brooks 1984). Setting aspects of the response in advance was shown to be beneficial to decrease the time for the central nervous system (CNS) to transform an incoming postural stimulus into an appropriate response (Horak et al. 1989). Jacobs and Horak (2007) have proposed that it may be that the cortex acts to prime or modulate postural response synergies whose circuitry is within the brainstem, thereby optimizing postural responses for a given environmental context, while still allowing for the early response latencies that are necessary for recovery of equilibrium.

The time to peak for ERP postural components (P1, N1, and P2) was not affected by the DT context as hypothesized. These results are similar to those that found no difference in N1 peak onset between ST and DT conditions (Quant et al. 2004). Although no P1 component was identified in the previous study, the positive peak following N1 also showed no attenuation in amplitude in ST versus DT conditions. Peak ERP components have been shown to vary in latency and scalp site across modalities. For example, the visual P1 is largest at lateral occipital electrode sites, with typical peak latency between 100 and 130 ms (Luck 2005). There are several visual N1 subcomponents, the earliest peaks approximately 100–150 ms post stimulus at anterior electrode sites and two posterior sites that typically peak 150–200 ms post stimulus, one arising from parietal cortex and another from lateral occipital cortex (Vogel and Luck 2000; Hopf et al. 2002). The visual P2 follows N1 at the anterior and central sites and peaks 180–220 ms post stimulus. The presence or absence of P2 and P3 is dependent upon scalp site and modality, (e.g., P3 is absent in the visual ERP, but typically seen after 300 ms in the auditory ERP) (Hillyard et al. 1998; Vogel and Luck 2000). The following peak onsets have been associated with ERP components in the postural literature, P1 (40–45 ms), N1 (100–160 ms), and P2 (250–300 ms) (Dietz et al. 1985; Quant et al. 2004, 2005; Mochizuki et al. 2009). Figure 2 shows that the postural P1 peak occurred 45–55 ms post stimulus, N1 at 110–150 ms, and P2 at 180–210 ms.

The variation in results may partly reflect (1) difference in measurement criteria (Dietz et al. (1985) measured the time to onset of the N1 peak, while others measured the

time of the maximum N1 peak), and (2) the difference in velocity of support surface perturbations for the studies, with faster velocities being associated with fast peak N1 times. For example, the current study and that by Dietz et al. (1985) used faster perturbation velocities (30 cm/s and a step change in treadmill speed from 0 to 6 km/h over a 70 ms period, respectively), while the studies by Quant et al. (2004, 2005) used slower perturbation velocities of 10 and 15 cm/s, respectively.

One of the strengths of the current study was the use of the change detection task. This task involves storage but not manipulation of information; this ensured that only one area of the cortex (posterior parietooccipital junction) was activated during the VWM task. Visual demands also remained constant between conditions; subjects were asked to focus on a cross that was projected on the monitor during ST conditions. To keep any additional motor requirements constant across conditions, subjects were instructed to randomly depress the buttons they held in their hands during the ST condition. Thus, any change in performance measures was associated with increased demands on attentional resources as opposed to increased motor demands.

A larger proportion of females than males were included in the current study, 11 and 3, respectively. Although some studies show a gender effect under DT conditions with OAs, others do not (Hollman et al. 2011; Wellmon 2012). The results from studies that have evaluated YA performance in DT contexts suggest that it is the modality targeted by the cognitive task that influences performance as opposed to gender (Saucier et al. 2003; McGowan and Duka 2000). Thus, the ambiguity seen across the age continuum with respect to the effect of gender on DT performance makes it difficult to comment on whether our outcomes may have been influenced by the disproportion of females to males in our study.

Although the current experimental paradigm was not set up to address the question of whether cortical and postural responses were scaled to increasing levels of cognitive challenge (set sizes 2 vs. 4 vs. 6), we predict that the more difficult the cognitive task the more attentional resources required for its accurate completion. It is unclear, however, whether postural versus cognitive performance is consistently given priority. In those subjects whose focus was on postural restoration, we would predict a larger drop in K for set size of 6 with limited modulation in postural response. Further evaluation of individual performance with respect to a focus on posture versus cognitive performance would be a valuable first step in determining the response patterns typically seen under DT conditions. We predict that it would be those subjects whose attentional resources were more limited that would demonstrate a scaling in their cortical and postural responses with increased cognitive challenge (set size 6).

As predicted, ERPs time locked to support surface perturbations were seen in electrode channels over several cortical regions, bilaterally over motor and sensory cortices. Since no significant difference in peak latencies was seen between ERPs over the motor and sensory cortical regions, we suspected a single localized source for these cortical ERPs. Based on animal models that show a correlation between activity of neurons in the motor cortex (intra-cranial neural recordings in rabbit) and EMG responses associated with the automatic postural response following tilts of the support surface, we postulate that the ERPs seen in the current study are associated with the motor cortex (Beloozerova et al. 2003).

This study examined attentional influences of a visual-spatial task requiring minimal information processing, on recovery of balance, following a perturbation. Even with this very specific secondary cognitive task, a reduction in the N1 ERP magnitude, associated with the automatic postural response, was found. We reasoned that because we used a secondary task that isolated a single region of the cortex that attenuation of the N1 amplitude was seen over a broad cortical region. As the N1 response has been hypothesized to be involved with sensory processing related to the postural perturbation, this suggests that the visual-spatial task interferes with this processing. Though the electrodes sampled in this study were situated over the sensory and motor cortices, we did not do a source localization analysis to determine the exact source of the ERP and therefore cannot verify whether it is associated with sensory processing, as has been previously hypothesized. Future research will examine this issue, to determine the exact source of the N1 ERP in this task.

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