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RESEARCH ARTICLE

Cortical activity modulations underlying age-related performance differences during posture–cognition dual tasking

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Abstract To date, no systematic research investigating cortical correlates of performance changes in dual tasking has been reported in the elderly population. Thus, we monitored whole-scalp cortical activations (EEG) during both single task and posture–cognition dual tasking with the main goal of understanding cortical activity modulations underlying age-related differences on posture–cognition dual tasking conditions. Postural and cognitive data analyses showed that elderly people had decreased cognitive performance even during challenging single cognitive tasks. Working memory impairments in the elderly group can be observed when a challenging cognitive task is performed in any postural condition, while postural control performance differences only became significant during challenging dual task conditions. Behavioral performance results, in general, indicate that elderly subjects may adopt a non-automated conscious control strategy and prioritize postural performance over cognitive performance to maintain upright stance only when the cognitive load is low. EEG analyses showed increased delta, theta and gamma oscillations, primarily over frontal, central-frontal, central and central-parietal cortices during dual tasking conditions. We found that delta oscillations were more responsive to challenging postural conditions presumably related to cortical representations of changing sensory conditions in postural tasks. Theta rhythms, on the other hand, were more responsive to cognitive task difficulty in both groups, with more pronounced increases in younger subjects which may underlie neural correlates of high-level cognitive computations including encoding and retrieval. Gamma oscillations also increased in the elderly primarily over central and central-parietal cortices during challenging postural tasks, indicating increased allocation of attentional sources to postural tasks.

Keywords Postural control · Aging · EEG · Time–frequency analyses · Dual task · Cognition · Working memory

Introduction

Most daily life activities require performing various motor and cognitive tasks concurrently and thus often involve continuous integration of multiple cognitive processes and neuromotor control systems. In such multi-tasking situations, upright stance is considered to be a baseline motor skill to accomplish a variety of goal-directed motor and cognitive tasks (Haddad et al. 2013). Although control of upright stance is a seemingly effortless and autonomous motor task predominantly governed by spinal and subcortical networks in the optimally functioning nervous system, it may become a challenging and attentionally demanding task with increased cognitive involvement at the cortical level, in the aging nervous system (Woollacott and Shumway-Cook 2002).

Dual tasking paradigms, originating from shared attention theory, have been commonly used to investigate

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attentional demands of postural control (Brauer et al. 2002; Brown et al. 1999) as well as the interaction between cognitive tasks and postural control performance in relation to aging (Boisgontier and Nougier 2013). A majority of studies indicated impaired performance in either postural, cognitive or both tasks during challenging dual task conditions (Doumas et al. 2009; Makizako et al. 2013; Olivier et al. 2010; Teasdale and Simoneau 2001; Van impe et al. 2013; Woollacott and Velde 2008). In regard to dual task cognitive performance, it has generally been reported that challenging postural tasks impair cognitive performance especially in the elderly people, as compared to healthy young adults (Brauer et al. 2001; Brown et al. 1999; Rapp et al. 2006; Redfern et al. 2001; Teasdale et al. 1993). The general consensus is that there is a shift in the control of upright stance from supra-spinally originated neural pathways to higher-order cortical networks in elderly people, suggesting that elderly people may recruit more cognitive sources than younger counterparts in a given postural task and thus exhibit impaired cognitive performance during challenging task conditions.

Many previous dual tasking studies also reported increased postural sway when attentional requirements of concurrently performed cognitive tasks exceed the total information processing capacity of the individual (Dault et al. 2001; Remaud et al. 2013). Decreased cognitive or postural performance during dual tasking in elderly people is generally attributed to the well-known deteriorative effects of aging on cognitive processing and sensorimotor functioning. For example, due to the impairments in sensorimotor tracts underlying the supra-spinally driven automatic posture control mechanisms, elderly people are assumed to rely more on high-level cortical processing loops as a compensatory strategy to control upright stance (Boisgontier and Nougier 2013). This requires increased allocation of cognitive resources for posture control tasks and, thus, is considered to lead to further performance impairments during dual tasking conditions due to the limited attentional capacity (Goble et al. 2010). Shared attention theory can fairly explain a variety of experimental results reporting increased center of mass (COM) sway when elderly people were asked to perform cognitive tasks (i.e., working memory task) during posture control testing (Berger and Bernard-Demanze 2011; Bernard-Demanze et al. 2009; Brown et al. 1999; Dault and Frank 2004; Granacher et al. 2011; Lajoie et al. 1996; Marsh and Geel 2000; Raymakers et al. 2005; Swan et al. 2004; Teasdale et al. 1993; Teasdale and Simoneau 2001). However, it also fails to account for recent research findings indicating either unchanged or decreased COM sway in older adults during dual tasking (Dromey et al. 2010; Melzer et al. 2001; Prado et al. 2007; Shumway-Cook et al. 1997; Van Impe et al. 2013; Weeks et al. 2003; Yogev-Seligmann et al. 2013).

Studies that report decreased COM sway in dual task settings attributed their findings to either “task prioritization model” or “facilitatory control” strategy employed by elderly people (Fraizer and Mitra 2008). The task prioritization model suggests that elderly people prefer tighter postural control strategy “posture first” during dual tasking conditions by prioritizing postural stability over cognitive performance with the main goal of preventing themselves from falling (Brauer et al. 2002). The facilitatory control hypothesis, on the other hand, assumes that postural control is a natural component of dual tasking since postural control mechanisms almost always coexist with numerous other cognitive functions (i.e., memory, language, spatial orientation) in daily life settings. This view, therefore, interprets the postural control system as a naturally integrated part of other cognitions and considers posture–cognition dual tasking as a single higher order rather than being an independent skill with autonomous components (Fraizer and Mitra 2008).

Most of these theoretical interpretations have been heavily based on behavioral performance observations without having neurophysiological evidence regarding the conflicting nature of dual tasking performance. To date, no systematic research investigating cortical correlates of performance changes in dual tasking has been reported in the elderly population. Thus, in this study we monitored whole-scalp cortical activations during both single task (cognitive only or posture only) and dual tasking with the main goal of understanding cortical activity modulations underlying age-related performance differences on posture–cognition dual tasking conditions. We designed a 2 (challenging/non-challenging cognitive task) by 2 (challenging/non-challenging postural task) experiment to (1) better understand age-related changes in dual tasking postural control performance along with (2) task-related cortical activity modulations. Regarding behavioral performance, we expected to find similar cognitive and postural performance between elderly and young subjects during non-challenging single or dual tasking conditions. Increased cognitive load, on the other hand, was expected to increase postural sway even during non-challenging postural tasks in the elderly people due to declined attentional capacity. As for the cortical activation patterns, we expected to observe increased cortical activity in elderly people during dual tasking conditions as a compensatory strategy due to increased attentional demands of postural control. Despite increased cortical activity, however, we expected to find similar postural and cognitive performance levels between elderly and young subjects when standing balance is not threatened during non-challenging postural and cognitive tasks.

Methods

Subjects

Ten healthy young (4 female and 6 male, $M_{age} = 26.20 \pm 2.77$ years) and 9 healthy older (6 female and 3 male, $M_{age} = 81.42 \pm 6.30$ years) adults participated in this study after reporting freedom from any neurological, cardiovascular, vestibular or musculoskeletal disorders, and no history of falls for at least 6 months prior to study. Overall health status of the prospective participants was assessed using the physical activity readiness questionnaire (PAR-Q) (Canadian Society for Exercise Physiology 2002). Cognitive functioning level of older adults was measured with the mini-mental state examination (MMSE; Folstein et al. 1975), and those who scored <27 were excluded from the study. All participants were informed about the experimental protocols before they gave their written consent. The study protocol was approved by the Institutional Review Board of the University of Houston.

Instrumentation

Center of pressure data (COP) for postural performance were quantified using standard computerized dynamic posturography platform (NeuroCom Balance Master, NeuroCom Intl, Clackamas OR) and used to estimate center of mass (COM) projections. The platform is equipped with a dynamic dual force plate system (18″ × 18″), in which ground reaction forces under the feet of individuals were collected at 100 Hz by four individual force transducers embedded within the force plate. Whole-scalp 64-channel EEG data were collected (actiCap system, Brain Products GmbH, Munich, Germany) and labeled in accordance with the extended 10–20 international system. EEG data were online referenced to channel FCz. Electrode impedances were maintained below 5 kΩ with a sampling rate of 1000 Hz. EEG signals were digitized using a BrainAmp DC amplifier linked to BrainVision Recorder software version 1.10. Cognitive performance was evaluated via series of working memory (WM) tasks. WM data were collected by using custom software that provides time-locked presentation of words. The custom software was developed using Microsoft Visual C++ and provides 26 alphabetic characters randomly which recognizes the participant's speech in real time.

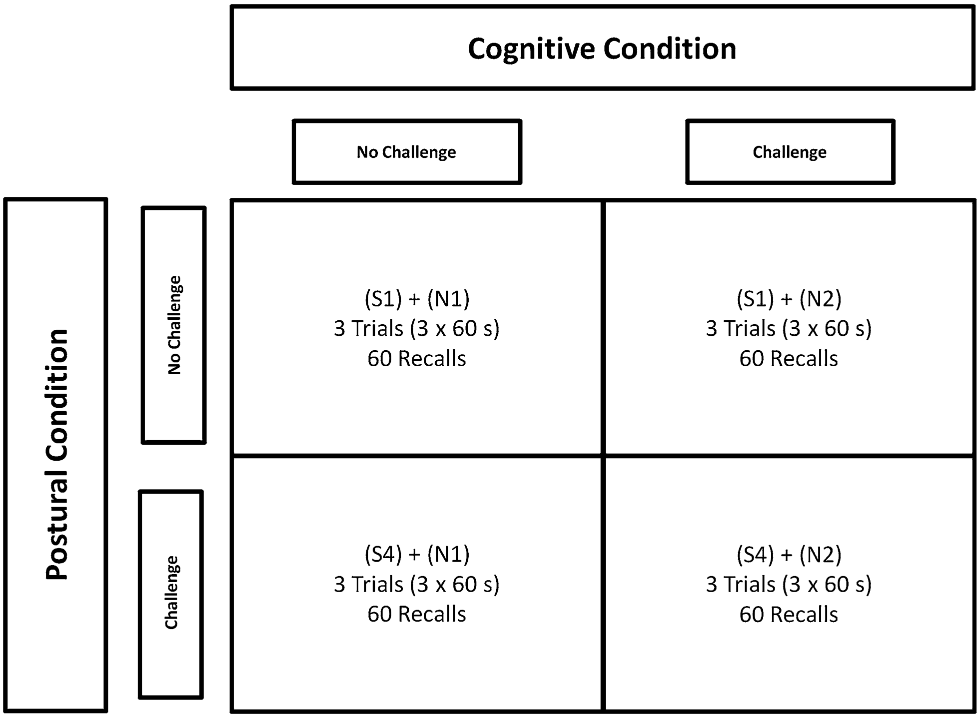
Experimental procedures

Prior to the beginning of WM trials, each subject was required to perform a familiarization procedure so that the custom-made software could better understand the participant's voice and intonation. The N-Back WM paradigm was employed audibly, and subjects were instructed to respond verbally. Specifically, subjects were presented with a series of words via headphones where the first word was presented at the beginning of each trial and subsequent words were presented with 3-s intervals. Subjects were asked to recall previously presented words depending on the N-back condition. In the one-back condition (N1), subjects were asked to immediately recall the word that was presented before the current one, whereas in the two-back condition (N2) subjects were required to recall the target word presented two stimuli ago in the row. The WM task was also synched to both the postural data (COM) and EEG monitoring systems during dual tasking conditions.

Each experiment trial started with single task conditions (balance task only and cognitive task only). For single balance tasks, participants were asked to perform quiet stance fixed platform surface (S1) as non-challenging and quiet stance sway platform surface (S4) as challenging balance task with their eyes open. Each single balance task was performed for 30 s. Single cognitive task conditions included one-back (N1) as non-challenging and two-back (N2) as challenging WM tasks. After completing the four single task conditions, a 2-by-2 experimental design was followed for posture control dual tasking measurements (Fig. 1). In the dual tasking paradigm, S1 and S4 balance tasks were concurrently performed with N1 (S1 + N1, S4 + N1) and N2 (S1 + N2, S4 + N2) cognitive tasks, respectively. Three trials, each lasting 60 s, were performed for dual tasking conditions. Twenty word recalls were performed during each trial, making 60 recalls in total for each dual tasking condition. The order of trials was randomized. During all postural tasks, subjects were instructed to focus on their WM task performance. The main purpose in directing focus of attention to cognitive instead of postural tasks was to examine postural control performance in an ecologically valid setting. In daily life functioning, we do not usually focus primarily on automatized motor skills such as posture control during multi-tasking activities (McNevin and Wulf 2002). Maintaining upright stance is not considered to be the main focus of attention unless standing balance is threatened. Thus, we aimed to investigate the effects of cognitive load on standing balance as it occurs in daily life settings in which people have to maintain upright stance without consciously focusing on their balance while performing other tasks.

Data reduction and signal processing

Posture control data processing steps were performed as explained in Ozdemir et al. (2013). Briefly, ground reaction force data collected from the Neurocom system were combined to create center of pressure (COP) time series in the anteroposterior (AP) and medial–lateral (ML)



		Cognitive Condition	
		No Challenge	Challenge
Postural Condition	No Challenge	(S1) + (N1) 3 Trials (3 x 60 s) 60 Recalls	(S1) + (N2) 3 Trials (3 x 60 s) 60 Recalls
	Challenge	(S4) + (N1) 3 Trials (3 x 60 s) 60 Recalls	(S4) + (N2) 3 Trials (3 x 60 s) 60 Recalls

Fig. 1 Dual tasking conditions

directions for each trial (Ozdemir et al. 2013). Corresponding center of mass (COM) position was estimated by low-pass filtering the COP data (second-order Butterworth; $f_c = .86$ Hz), and COM velocity was estimated by differentiating the COM position using a 3-point central difference algorithm. Stability boundaries in the AP and ML directions were conservatively estimated at the outer extremes of the foot locations to create a rectangular stability zone for each subject, and distance to boundary (DTB) was estimated as the instantaneous differences between the COM position and the stability boundaries in the direction of COM movement. Time to boundary (TTB) time series were then calculated by dividing the DTB by the COM velocity for each direction. Two performance measures were derived from the TTB time series for each trial. The minimum value of the TTB over each trial (TTB-min) represents the least stable moment during the trial and was considered to be the worst-case performance during the trial. The integrated area of TTB (iTTB) was also calculated below an arbitrary 10-s threshold that represents an estimate of relative instability over the entire trial. iTTB is expressed as a fraction of the total area beneath the threshold during the trial.

The EEG data were processed offline using EEGLAB 5.03 (Delorme and Makeig 2004) and MATLAB open-source toolbox (Mathworks, Natick, USA). First, independent component analyses (ICA) were performed on the raw data to identify and remove components related to potential mechanical artifacts and eye blinks for all channels. The EEG channels from the peripheral and temporal sites (FP1–2, AF7–8, F7–8, FT7–10, T7–8, TP7–10, P7–8, PO7–8, PO9–10, in the extended 10–20 EEG system montage) were rejected and not used in any further analyses due to their sensitivity to a number of physiological artifacts including facial gestures, eye movements or cranial muscular activity. The EEG data were then band-pass filtered with a zero-phase third-order Butterworth filter from .1 to 50 Hz for main analyses. Next, each EEG channel was standardized by subtracting the mean and dividing by its standard deviation (Cruz-Garza et al. 2014).

For main analyses, a continuous complex Morlet wavelet transform (CWT) was performed to quantify modulation of EEG signal power within delta (1–4 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (14–24 Hz) and gamma (30–50 Hz) bands over time throughout the duration of the postural trials (Slobounov et al. 2009). Specifically, EEG data were down sampled to 100 Hz and the MATLAB wavelet toolbox including CWT algorithms was used to compute a two-dimensional representation of time–frequency energy of raw EEG data from low delta (0.2 Hz) to high gamma (50 Hz) oscillations. Then mean energy power in the time–frequency series was calculated for every 1 s (100 data points) for each EEG channel, representing continuous modulations in EEG signals within the postural condition. Finally, a grand mean energy power was calculated from one-second time–frequency energy means representing relative power changes in EEG channels across the entire duration of a given postural condition.

As for the WM tests, response time (RT) in seconds and response accuracy (RA) in percentages were measured to quantify cognitive performance. RA was calculated as the ratio of number of correct responses to total number of responses. RT analyses were also performed for both correct and incorrect responses.

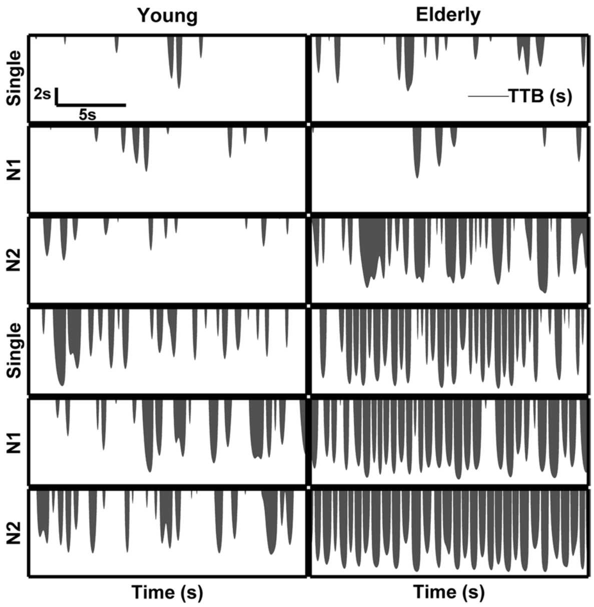


Fig. 2 TTB time series for single task postural (S1 and S4) and dual tasking postural plus working memory (N1 and N2) conditions in representative young (*left*) and elderly (*right*) subjects

Statistical analyses

A series of 2 × 3 mixed-design repeated-measures ANOVA with group (young vs elderly), as the between-subject factor, and condition (N-back single vs N-back SOT1 vs N-back SOT4), as the within-subject factor, were conducted to examine effects of cognitive tasks on postural performance. Simple effect analyses with Bonferroni corrections ($p = .05$/number of comparisons) were performed to understand group differences among conditions. Similarly, the effect of postural task on cognitive performance was also tested with series of 2 × 3 mixed-design ANOVA.

For statistical analyses of EEG data, cortical regions of interest (ROIs) were defined by calculating the grand mean EEG powers across all subjects, in each group, and channels for different cerebral regions including the frontal (F3, F1, Fz, F2, F4), central-frontal (FC5, FC3, FC1, FC2, FC4, FC6), central (C3, C1, Cz, C2, C4), central-parietal (CP3, CP1, CPz, CP2, CP4) and parietal (P3, P1, Pz, P2, P4) cortices. A series of 2 (group: elderly vs young) × 2(condition: single task vs dual task) repeated-measures variance analyses were performed to examine changes in grand mean EEG power in ROIs across groups and postural conditions for each frequency band.

Results

Postural performance

Figure 2 shows postural performance as TTB time series during both single (postural only) and dual tasking conditions for a representative young and elderly subject. During single postural tasks (S1 panels and S4 panels), especially during the non-challenging posture task, S1, similar postural sway characteristics were observed for the elderly and the young subject. This was also true when subjects were performing dual tasking with the two non-challenging conditions (S1/N1). However, when subjects were performing dual tasking containing either (S1/N2 or S4/N2) of the challenging conditions, postural sway increased considerably more in the elderly subject than the young subject, indicating limited cognitive capacity in the elderly when compared to single task conditions.

Figure 3 shows group means (±SD) for postural and cognitive performance during single and dual task conditions. Mixed-design repeated-measures variance analyses for S1 trials showed a significant multivariate effect for TTBmin across dual tasking conditions (S1/N1 and S1/N2; $p = .029$). Follow-up paired sample comparisons revealed that TTBmin was significantly ($p = .041$) higher for the S1/N1 dual task when compared to the S1 single task, indicating improved balance performance during low-cognitive load dual tasking condition in both groups. For the more challenging S1/N2 dual task condition, TTBmin values decreased ($p = .010$) in the elderly group, but not in the young group when compared to S1/N1 dual task condition, suggesting that the elderly group relied more heavily on cognitive resources to maintain upright stance, even under nonthreatening conditions. Repeated-measures ANOVA for S4 trials showed no significant within-subject change in TTBmin across dual tasking conditions in both groups ($p > .05$). Group comparisons, on the other hand, indicated poor balance performance for elderly group during the S4/N1 dual task conditions compared to young group ($p = .042$). No significant group difference was found also for TTBmin values during the S4/N2 dual task condition.

iTTB analyses for S1 trials showed significant condition effect ($p = .004$) and "group × condition" ($p = .004$) interaction effect across dual tasking conditions. Follow-up paired sample comparisons revealed that iTTB values significantly decreased ($p = .021$) from S1 single task to S1 + N1 dual tasking condition and, however, significantly increased ($p = .003$) from S1 + N1 to S1 + N2 dual tasking condition in the elderly group, indicating increased postural sway for the entire postural trial during challenging cognitive conditions. Nonsignificant condition effect

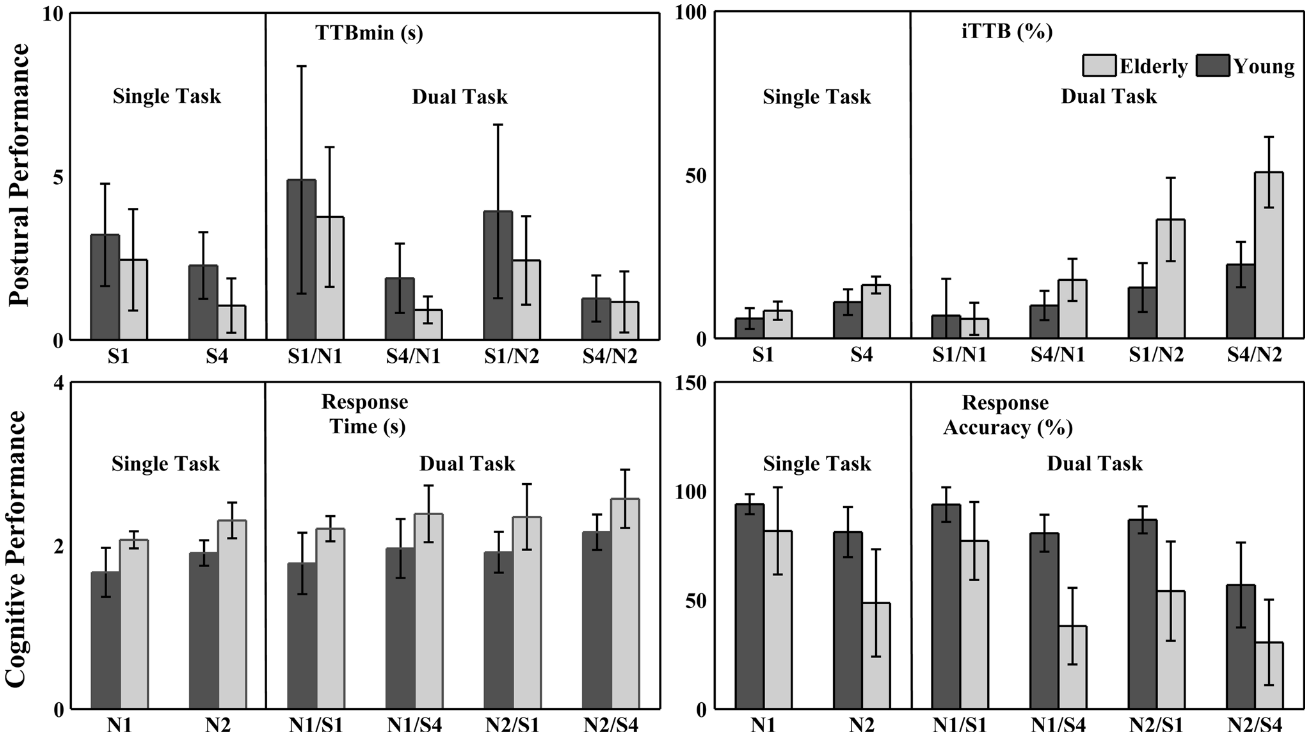


Fig. 3 Postural (TTBmin, iTTB) and cognitive (response time, response accuracy) performance (mean ± SD) for young and elderly subject groups during single and dual tasking conditions

($p > .05$) for the young group, on the other hand, suggests that, despite challenging cognitive condition, postural sway did not increase across dual tasking trials (Fig. 3). Simple effect analyses were performed to break down "group × condition" interaction effects by comparing iTTB differences between groups at each postural condition (Field 2009). Simple effect analyses showed that elderly subjects have higher iTTB ($p = .009$) than their younger counterparts at S1 + N2 dual tasking condition indicating increased postural sway even at fixed platform postural task when they performed a challenging cognitive task. For S4 trials, repeated-measures analyses revealed significant condition effect ($p = .000$) and "group × condition" interaction effect ($p = .000$). Follow-up paired sample comparisons for condition effect showed remarkably increased iTTB in the elderly group from S4 + N1 to S4 + N2 ($p = .000$) dual tasking conditions (Fig. 3). Follow-up analyses in the young group, on the other hand, only showed significant iTTB differences between S4 single and S4 + N2 dual tasking conditions ($p = .021$).

Cognitive performance

Repeated-measures analyses showed significant condition effect ($p = .000$) for response time (RT) values at N1 trials. RT was longer only during N1 + S4 dual tasking condition in both groups (Fig. 3) when compared to N1 single tasking. No significant "group × condition" effect ($p > .05$) was found, but group comparisons indicated faster RT performance for the young group both during single ($p < .05$) and dual tasking ($p < .05$) trials (Fig. 3). Response accuracy (RA) analyses, on the other hand, indicated a significant interaction effect ($p = .021$) for N1 trials (Fig. 3). Follow-up comparisons showed declined RA only in the elderly group during N1 + S4 dual tasking when compared to both N1 single ($p = .000$) and N1 + S1 ($p = .002$) dual tasking conditions, indicating even low cognitive loads can be demanding during challenging postural conditions. No condition effect was found in the young group ($p > .05$) that younger subject can maintain similar cognitive performance across dual tasking conditions (Fig. 3). Compared to the elderly group, RA was also higher in the young group ($p < .05$) in both N1 single and dual tasking conditions.

For the challenging N2 cognitive trials, RT significantly increased ($p = .001$) from N2 single to N2 + S4 dual tasking conditions in both groups (Fig. 3). RT was also found to be longer in the elderly group ($p < .05$) when compared to the young group in N2 conditions. Response accuracy analyses also revealed significant condition effect ($p = .002$). Follow-up comparisons showed that RA significantly declined from N2 single task to N2 + S4 dual tasking conditions ($p = .041$) in the elderly group (Fig. 3). No significant RA differences ($p > .05$) were found between N2 single and N2 + S1 dual tasking conditions in the young group. Declined RA performance was only observed during N2 + S4 dual tasking conditions in the young group, indicating that challenging postural task also effect cognitive performance in young subjects (Fig. 3).

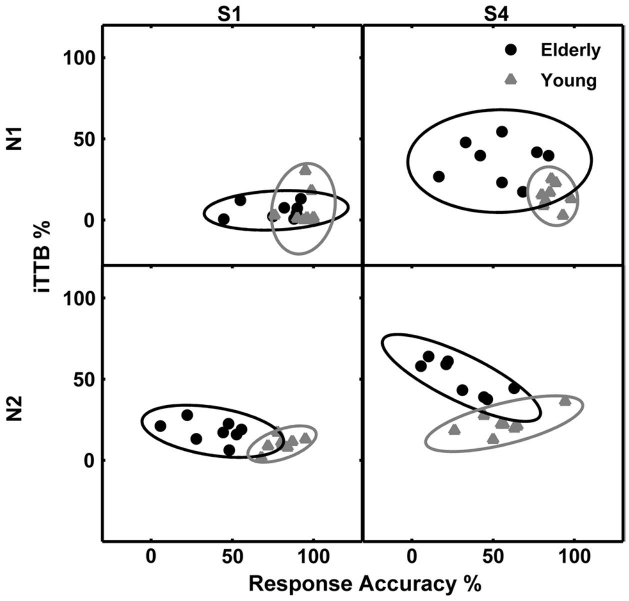


Fig. 4 Bivariate scatter plots (*circles* represents area with 2 standard deviations for the given data set) for iTTB (postural performance) and response accuracy (cognitive performance) for both the elderly and the young group during dual tasking conditions

To better understand cognitive and postural performance interactions, bivariate scatter plots with standard deviation areas were computed for iTTB and RA and are presented in Fig. 4. In general, scatter plots indicated that non-challenging dual tasking condition (S1/N1) does not differentiate groups, but when dual tasking includes any challenging condition (either cognitive or postural) performance differences become more evident between the groups (Fig. 4). One important observation is the significant negative correlation ($r = .66$, $p < .05$) between iTTB and RA during S4 + N2 dual tasking condition in the elderly group that individuals with high cognitive capacity have reduced postural sway, suggesting the important role of sustained attentional sources on postural performance during challenging dual tasking conditions (Fig. 4).

Cortical activity modulations during dual tasking

Topographical distribution of group means of EEG power in delta, theta, alpha and gamma waves was plotted as scalp maps to show how EEG power is modulated over the entire scalp across different cognitive-postural dual tasking conditions (Fig. 5). Delta activity seems to increase in both groups, especially over the frontal, central-frontal and central regions, only when dual tasking includes challenging postural condition (S4) with a more pronounced increase in the young group (Fig. 5, first column). Theta band EEG activity, on the other hand, seems to be more responsive to working memory performance during dual tasking conditions with challenging cognitive tasks (N2) in both groups over frontal, central-frontal and central cortices (Fig. 5, third and fourth columns). Increased alpha activity was also

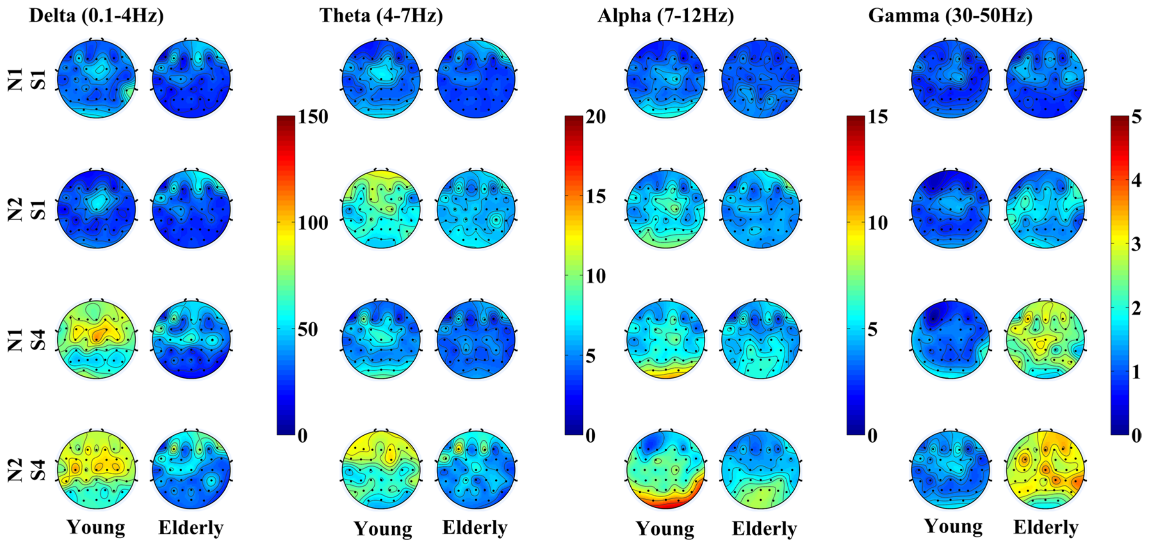


Fig. 5 Scalp maps of group mean EEG power for delta, theta, alpha and gamma bands under the four experimental conditions for young and elderly subjects

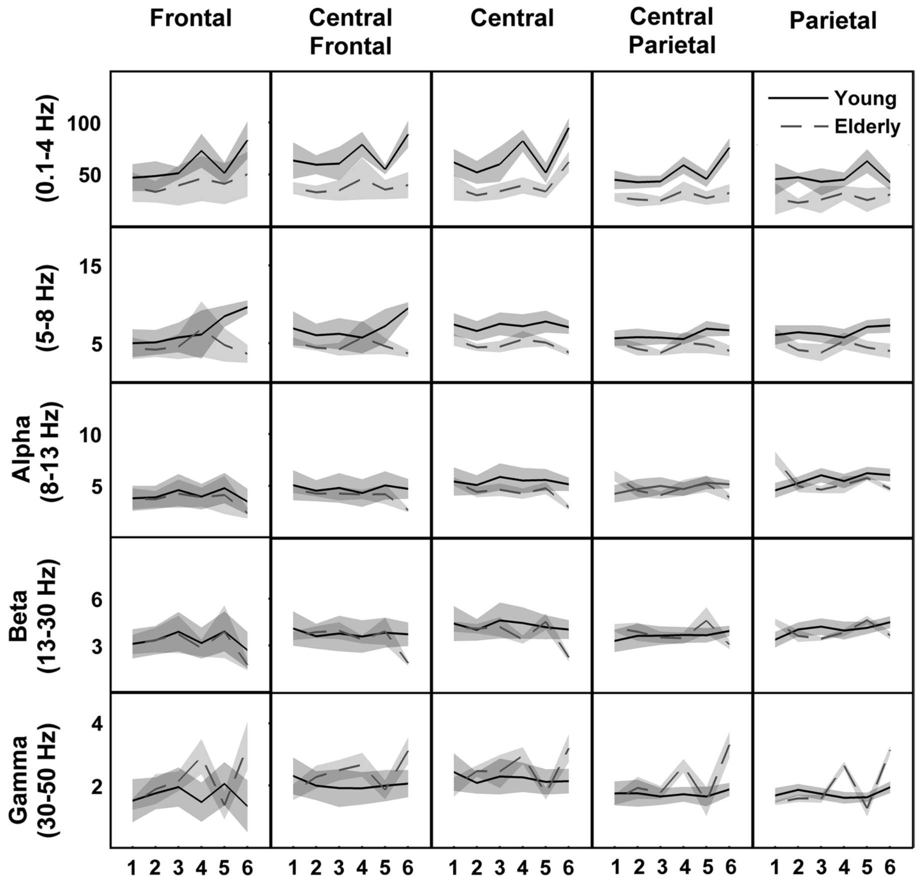


Fig. 6 Group means (young = *solid lines*; elderly = *dashed lines*) and standard deviations (*shaded regions*) of EEG activity for each ROI at different frequency bands and across dual tasking conditions: 1 = N1, 2 = N2, 3 = N1/S1, 4 = N1/S4, 5 = N2/S1 and 6 = N2/S4

observed over parietal and occipital cortices in both groups with increasing dual tasking difficulty. Increased alpha is, however, more pronounced in the young group especially over occipital cortices during N1 + S4 and N2 + S4 dual tasking conditions (Fig. 5, column 5). As for the gamma band, increased activity was observed only in the elderly group especially over central and central-parietal cortices during dual tasking conditions with challenging (S4) postural control tasks (Fig. 5, column 8).

Figure 6 shows group means and standard deviations of EEG activity for each ROI at different frequency bands and across dual tasking conditions. Repeated-measures variance analyses were performed to examine changes in grand mean EEG power in ROIs across groups and postural conditions for each frequency band. For delta band analyses, results showed significant main effect for dual tasking conditions over frontal ($p = .040$), central-frontal ($p = .044$), central ($p = .037$) and central-parietal regions ($p = .033$). Pairwise comparisons with Bonferroni corrections indicated significantly increased delta activity during N1 + S4 and N2 + S4 dual tasking conditions, when compared to single cognitive (N1 and N2) and dual conditions with non-challenging postural tasks (S1) at central-frontal ($p < .05$), central ($p < .05$) and central-parietal ($p < .05$) regions in the young group (Fig. 6, upper panels). The elderly group also showed increased delta during N1 + S2 dual tasking condition at the central region ($p < .05$). Although, in general, the young group had higher delta activity across all experimental conditions and ROIs, significant differences were only found during dual tasking with challenging postural tasks (S4) in all ROIs, when compared to the elderly group.

Theta band EEG activity was found to be significantly higher during dual tasking with challenging cognitive task conditions (N2 + S1 and N2 + S4) over frontal ($p = .039$) and central-frontal ($p = .044$) regions when compared to single cognitive tasks and dual tasking with non-challenging cognitive task conditions (Fig. 6). Group comparisons also showed higher theta activity in the young group over frontal ($p < .05$) and central-frontal ($p < .05$) regions during challenging cognitive dual tasking conditions, when compared to the elderly group. Significant increases in alpha activity were observed in both groups over central-parietal and parietal regions during dual tasking conditions with challenging postural conditions (N1 + S4 and N2 + S4). Similarly, group comparisons indicated higher alpha activity increases over parietal region during challenging cognitive and dual tasking (N2 + S4) conditions (Fig. 6, third row panels). No significant differences were observed for beta activity ($p > .05$) across experimental conditions and groups (Fig. 6). Gamma band activity, however, was found to be higher in the elderly group over frontal ($p = .042$), central-parietal ($p = .029$) and parietal regions ($p = .026$) during dual tasking with challenging postural control task conditions (Fig. 6).

Discussion

The main objective of this study was to better understand age-related changes in dual tasking postural control performance along with task-related cortical activity modulations. In general, our results are in line with most of the previous studies reporting impaired performance during challenging posture-dual tasking conditions in the elderly population (Brauer et al. 2001; Brown et al. 1999; Rapp et al. 2006; Redfern et al. 2001; Shumway-Cook and Woollacott 2000; Teasdale et al. 1993). Postural and cognitive data analyses showed elderly people had no performance deficits during single postural task conditions (single S1 and S4), but decreased response accuracy even during challenging single cognitive tasks (single N2). Dual tasking analyses mainly indicated that working memory impairments in the elderly group occurred when a challenging cognitive task (N2) was performed in any postural condition (either S1 or S4), but postural control performance differences only became significant during dual tasking with challenging postural and cognitive (N2 + S4) task conditions (Fig. 3). During challenging postural and cognitive dual tasking, we also noticed that elderly subjects with high cognitive capacity exhibited less postural sway during the entire trial (Fig. 4). Our EEG analyses showed increased delta, theta and gamma oscillations, primarily over frontal, central-frontal, central and central-parietal cortices during challenging dual tasking conditions (Fig. 5). To the best of our knowledge, this study is also the first to show age-related differences in cortical activation patterns during dual tasking. We found that delta oscillations were more responsive to challenging postural conditions presumably related to cortical representations of changing sensory conditions in postural tasks. Theta rhythms, on the other hand, were more responsive to cognitive task difficulty in both groups, with more pronounced increases in younger subjects which may underlie neural correlates of high-level cognitive computations including encoding and retrieval. Gamma oscillations also appeared to increase in the elderly group primarily over central and central-parietal cortices only when dual tasking is performed with a challenging postural task, indicating increased allocation of attentional sources to postural tasks.

Age-related changes in cognitive and postural performance during dual tasking conditions

Despite inconsistent findings in the posture control-related dual tasking literature (for details, see recent review by Boisgontier and Nougier 2013), one strong consensus derived from many studies is that posture control and higher-order cognitive skills share common attentional resources (Fraizer and Mitra 2008), and decrements in cognitive performance during dual tasking can be explained by impaired cognition in elderly people (Woollacott and Shumway-Cook 2002). Our results regarding cognitive performance difference between young and elderly subjects also suggest decreased attentional capacity in the elderly such that, even during single task conditions, response accuracy was lower in the elderly group when the high-cognitive load (N2) task was performed. We also found that although there was no performance difference between the groups for a non-challenging cognitive task during single (N1) and non-challenging dual tasking (N1 + S1), decreased cognitive performance in N1 was observed only in the elderly group when they concurrently performed N1 with a challenging postural task (N1 + S4). These results suggest that a challenging postural task requires more attentional sources in the elderly, as compared to the young group; thus, it can further impairs cognitive performance even for low-cognitive load tasks during dual tasking. Decreased cognitive performance during challenging postural conditions in the elderly group may also reflect that elderly people may prioritize balance performance and thus intentionally allocate more cognitive sources to postural tasks when upright stance is threatened (Fig. 3, response accuracy panel, notice group differences in N1 and N1 + S1 vs N1 + S4 conditions).

Our results for postural performance, on the other hand, seem to support both "shared attention or capacity" theory and "facilitatory control" hypothesis depending on the challenging nature of dual tasking conditions. Increased postural sway and decreased response accuracy in both groups during dual tasking with challenging postural task (N2 + S4) conditions suggested that concurrent performing of high-load cognitive task (N2) with a sway platform postural task (S4) may challenge available attentional resources and impairs both cognitive and postural performance. Decreased dual tasking performance was also more dramatic in the elderly group presumably due to reduced capacity in overall cognition.

Supporting evidence for "facilitation hypothesis" comes from non-challenging dual tasking conditions that, compared to single postural task performance (S1), concurrent low-load cognitive task (N1) increases TTBmin (Fig. 3, TTBmin panel) and slightly decreases iTTB (Fig. 3, iTTB panel), indicating reduced sway during a fixed platform (S1) postural task. This facilitatory effect of concurrent N1 task on postural performance, however, disappears during sway platform conditions (N1 + S4), suggesting that a non-challenging cognitive task may facilitate postural performance only during natural standing (S1) conditions. Previous research tends to explain facilitatory effects of simple cognitive task on postural performance by the functional role of upright stance in everyday posture–cognition tasks. According to this understanding, postural control for functional activities in daily life settings is mostly used as a primary tool to achieve variety of perceptual or motor tasks which often require certain degree of cognitive processing. This suggests that lifelong acquired automated postural skills such as natural standing on a fixed surface might be presumably well integrated with cognitive faculties and, thus, do not pose further challenge to the posture control system.

Another possible explanation could be attributed to methodological issues such that, in our study, we asked subjects to perform their best for recalling words in the working memory task during dual tasking. The main purpose was to mimic ecological settings and quantify postural performance as it is performed in daily life contexts. During single postural tasks, alternatively, subjects may consciously focus on their standing balance which has been shown to negatively interfere with well-automated processes underlying postural control (for details, see Fraizer and Mitra 2008). Contrarily, release of attention from postural tasks by employing an external focus or switching attention from postural to secondary tasks has been shown to enhance postural stability (Vuillerme and Nafati 2007). Thus, future studies can also manipulate task instructions to better understand underlying mechanisms of enhanced postural performance during non-challenging dual tasking.

Modulated cortical activity during dual tasking

Many recent studies have investigated neural correlates of human upright stance and reported modulated cortical activity at different frequency bands during challenging postural conditions in healthy young adults (Slobounov et al. 2005a, b, 2008, 2009; Sipp et al. 2013). In particular, increased theta power over anterior parietal, frontal and sensorimotor cortices during challenging postural tasks (Hülsdünker et al. 2015; Sipp et al. 2013) and increased gamma activity over parietal cortices during unstable balance moments were reported (Slobounov et al. 2005a, 2009). Our EEG results are predominantly in line with previous reports that we found increased cortical activity in theta and gamma oscillations as a function of task difficulty. However, we were also able to examine age- and dual tasking-related cortical activity modulations during challenging and non-challenging postural conditions, which have not been reported previously. In regard to dual tasking conditions, theta activity was found to be responsive to cognitive task difficulty such that increased theta was predominantly observed during challenging cognitive dual tasking (N2) conditions over frontal and central-frontal cortices with more pronounced increases in the young group. Recent reports in neurocognitive studies have related increased theta oscillations over frontal brain areas to high-level cognitive computations including cognitive mapping during spatial navigation (Lithfous et al. 2015), memory encoding and retrieval during working memory tasks (Jensen and Tesche 2002), novelty detection and error monitoring during learning tasks (Cavanagh and Zambrano-Vazquez 2013). Previous postural control studies also reported significantly higher spectral power in theta oscillations located over anterior cingulate, medial sensorimotor cortex during loss of walking or standing balance (Sipp et al. 2013, Slobounov et al. 2009). In regard to standing balance, increased dorsolateral and prefrontal theta is considered to originate especially from the anterior cingulate cortex and assumed to have a functional role on sensory information integration and error detection related to decision-making mechanisms in internal feed-forward models of posture control (Ahmed and Ashton-Miller 2005, 2004, 2007). Our findings, however, indicated increased theta activity over central-frontal brain areas only during dual tasks with challenging cognitive, but not during challenging postural conditions. We also found that this increased theta is more pronounced in the young group, as compared to the elderly group, who also had higher WM performance for challenging (N2) tasks. Considering the fact that our challenging postural condition (S4) did not lead to loss of balance in the young group, increased theta activity seems to reflect demanding cognitive computations for memory encoding and retrieval functions when performing N2 working memory tasks concurrently with postural tasks. Indeed, a recent study on neural correlates of cognitive mapping for spatial navigation tasks found a significant correlation between increased theta and accuracy of cognitive mapping only in young but not in elderly subjects, due to reduced theta power during encoding in the elderly group (Lithfous et al. 2015).

Our findings for modulated gamma activity differences between the groups may also reflect increased attentional demands for challenging postural conditions in the elderly group. In general, fast oscillations in the cortex (>30 Hz) are considered to be related to focal neural computations due to shorter temporal processing windows at high frequencies (Harmony 2013). Regarding functional correlates of cortical processing, modulations in gamma power are attributed to focused arousal and sustained attention during both cognitive and motor tasks (Slobounov et al. 2005a, 2009). Considering our findings for continuous balance tasks, increased gamma power among older adults during challenging postural conditions, thus, may reflect increased allocation of attentional sources to postural tasks as compared to healthy young adults.

Apart from increased power in theta and gamma oscillations, however, we also found significantly higher delta band activity over central-frontal, central and central-parietal cortices during dual tasking with challenging postural conditions (Fig. 5). Although previous studies on cortical control of human stance have mostly reported EEG modulations in the theta band (4–7 Hz) and higher frequencies, our results regarding delta band modulations corroborate with recent research showing involvement of slow cortical oscillations in the control of coordinated multi-joint movements (Agashe and Contreras-Vidal 2013; Bradberry et al. 2010; Bulea et al. 2014; Gwin et al. 2010; Presacco et al. 2011). In particular, recent research focusing on understanding neural signatures of movement control during various multi-joint tasks has consistently associated changes in delta band oscillations with planning and execution of coordinated body movements. It has been, for example, reported that low-frequency EEG activations represent control parameters for various kinematics including direction (Liao et al. 2007; Vuckovic and Sepulveda 2008; Robinson et al. 2013; Waldert et al. 2008), velocity (Bradberry et al. 2010) and type (Agashe and Contreras-Vidal 2013) of multi-joint upper extremity movements. Regarding locomotion tasks, delta band oscillations have been shown to contain information about movement kinematics such that lower limb trajectories can be predicted and reconstructed by using delta band EEG with reasonably well accuracies up to 80 % during continuous walking (Bradberry et al. 2011; Presacco et al. 2011) and running (Gwin et al. 2010). In another line of research, pre-movement delta band signal features were extracted to successfully classify upcoming locomotive movement intentions such as start and stop walking (Kilicarslan et al. 2013) and "sit to stand" or "stand to sit" posture transitions preceding walking (Bulea et al. 2014). Our results, which showed modulated EEG in delta band during challenging postural conditions, also support these findings and provide preliminary evidence that slow EEG oscillations as low as 1–2 Hz can also be sensitive to the changes in postural state of the body and involve in controlling sensorimotor aspects of human upright stance.

Regarding group differences, younger adults had slightly higher cerebral delta activations particularly over sensorimotor cortices in central regions and dorsolateral prefrontal cortices in central-frontal electrode sites. Currently, however, we do not have clear understanding regarding the underlying neuromotor mechanisms of age-related differences in posture control-related delta activity, except that these slow cortical potentials are related to motor intent or movement (Bradberry et al. 2010; Bulea et al. 2014; Gwin et al. 2010; Presacco et al. 2011; but see discussion below). One possible reason for relatively low delta activity in older adults could be attributed to functional declines in sensorimotor processing due to aging (Andrews-Hanna et al. 2007). We should mention that continuously challenging postural tasks (60 s of challenging posture–cognition dual tasking condition) require considerable amount of perceptual integration and, thus, continuous synchronization of many distant neural networks in order to detect constantly changes in upright stance orientation in relation to the gravitational vector. In such demanding perceptual conditions, delta activity has been considered as a part of an inhibitory cognitive state that is involved in synchronization of distant neural networks (Harmony 2013). It has been postulated that sustained delta activity during cognitively demanding tasks would selectively suppress non-relevant neural networks through functional connectivity at the global scale and, thus, inhibit neural activity that may distract or interfere with proficient execution of perceptual tasks (Harmony 2013). Considering the possibility that even disease-free normal aging is accompanied by declined coordination among large-scale cortical connections, due to degenerations in white matter integrity (Andrews-Hanna et al. 2007), it is reasonable to conclude that these structural deformations may also be reflected by age-associated changes in delta band activity during cognitively demanding motor tasks.

Limitations and future directions

Although our study provided novel findings regarding cortical correlates of aging-related changes in posture control dual tasking performance, results should be interpreted with caution due to certain limitations. First, we only selected healthy older adults with limited sample size and no history of falls or neurological disorders for this study. Thus, our results regarding cortical correlates of upright stance control cannot be generalized to elderly fallers or individuals with pathological postural control deficits. We also found that our EEG data during dual tasking conditions were highly contaminated with EMG artifacts due to the use of auditory mode for the working memory task. Verbal responses with high volume created facial EMG artifacts predominantly over temporal and frontal channels during response periods and may contaminate EEG data especially at high gamma (30–50 Hz) frequencies. Despite the presence of EMG on raw EEG, however, we were able to identify and remove EMG artifacts through ICA and following preprocessing procedures; thus, its very unlikely that processed EEG signals especially on delta, theta, alpha and beta frequencies include remaining EMG artifacts.

Considering these limitations, therefore, future studies should target clinical populations with larger sample size and should employ nonverbal cognitive task conditions.

Conclusion

In conclusion, our results, for the first time, revealed cortical activity modulations underlying age-related performance differences during dual tasking conditions. We found that cognitive performance declines in the non-faller elderly group either (1) when they performed a challenging cognitive task or (2) when they performed a non-challenging cognitive task (N1) concurrently with a challenging postural task (S4). Postural performance, on the other hand, was only impaired when elderly people performed postural tasks (either S1 or S4) concurrently with a challenging cognitive task (N2). These results suggest that elderly subjects may adopt a non-automated conscious control strategy that prioritizes postural performance over cognitive performance to maintain upright stance when the cognitive load is low. When the cognitive load was high, on the other hand, the elderly subjects were not able to control their balance well, as evidenced by dramatically increased postural sway and high risk of falling. Regarding the cortical basis of age-related performance differences during dual tasking conditions, EEG analyses suggest that while increased theta over frontal and central-frontal cortices may underlie the cortical correlates of high-level cognitive computations including encoding and retrieval for working memory tasks, delta oscillations, in general, maybe underlie cortical monitoring of changes in postural state when sensory conditions of upright stance are compromised. Future studies should consider the limitations of this study.

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Compliance with ethical standards

Conflict of interest None of the authors has any financial or personal conflicts of interest in relation to the submission, other people or any organizations.

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