Abstract

Background. A range of cognitive tasks can interfere with postural control, particularly in older adults. In the case of spatial tasks, the spatial alignment between the task and postural control can incur dual-task costs separately from task load. It has been suggested that spatial tasks incur dual-task costs because accessing the visuospatial sketchpad component of working memory reduces the capacity to utilize external visual information for postural control.

Research question. We investigated whether the spatial alignment between a cognitive and postural control task can affect postural stability even when visual perception is not involved in either task and task load does not differ between aligned and non-aligned conditions. We predicted that any such effect would be greater in older people and in a more challenging stance.

Methods. Fifty healthy adults (27 aged 20-35, 23 aged 59-88) with no history of balance or cognitive difficulties performed a mental navigation task while standing in open or closed stance with eyes closed. The mental navigation task was presented in a reference plane that was either aligned or non-aligned to the horizontal reference plane in which the posture control system controlled the position of the body's center of gravity. Task performance was measured as accuracy and response time and postural sway as anteroposterior (AP) and mediolateral (ML) sway velocity.

Results. The older group were less accurate in the mental navigation task, and both groups had higher AP and ML sway velocity in closed stance. The older group standing in the more challenging stance had higher AP sway velocity while performing the mental navigation task in the non-aligned than the aligned reference plane condition.

Significance. The spatial configuration compatibility between a cognitive task and postural control can affect postural stability even when visual information is not being used for either task and task load is unchanged.

Keywords: posture control, dual-tasking, spatial memory, spatial imagery, aging

1. Introduction

Postural control and concurrent cognitive tasks can exhibit complex interactions whereby cognitive load can impact stance stability or recovery from perturbation and balance challenges can affect cognitive task accuracy [1,2]. These interactions have been considered the result of both tasks drawing on capacity-limited cognitive resources [1,3,4]. Some authors posit simultaneous demands on a limited pool of general resources [5,6], while others point to structural limitations in spatial information processing [7-9] or sensory integration [10,11].

An important consideration in this context is the dual role that postural control itself plays in maintaining balance while facilitating suprapostural tasks [12]. Depending on task demands, this dual role may functionally link postural control with aspects of suprapostural task performance [13]. If the cognitive task requires reading, for example, postural control may work to reduce head motion to facilitate precise eye fixation [14]. Thus, how well a posture-cognition dual-task is performed may depend not only on task loads but also on the extent to which the cognitive task's context can be embedded within the behavioral context provided by posture control [15].

The task context of a spatial cognitive task is the reference frame in which its operations are represented. If the spatial context for postural control is an earth-fixed reference frame, the relationship between it and the cognitive task's reference frame affects the extent to which the task can be layered over ongoing postural control actions. Fraizer and Mitra [15] showed that standing upright and visually searching for a target that appeared in a reference frame anchored to the swaying body increased body sway variability relative to searching for the same target presented in the posture control system’s earth-fixed reference frame. This dual-task interaction remained even when the placement of search items spanning the two reference frames controlled for the optic flow available to guide stance control. Importantly, the effects of reference frame alignment were in addition to those of the search task’s load (the size of the search set).

Fraizer and Mitra’s [15] visual search task was functionally linked to their balancing task in that the visual system contributed to both body sway detection and target search. Placing these two visual functions in non-aligned reference frames presented a perceptual conflict in the use of the same stimuli. The authors suggested that this configurational incompatibility between the tasks’ spatial contexts meant that performance costs arose in the need to maintain both reference frames and to keep them in register to prevent disorientation. As they only studied a perceptual task, it was unclear whether their proposed configurational incompatibility effect applies only to perceptual tasks or to spatial cognition more generally.

A reference frame is just as critical to spatial memory or imagery tasks [16]. Here, we studied the impact on the postural sway of healthy young and older adults when they performed a mental navigation task set on a reference plane that was spatially aligned or non-aligned to the reference plane of the balancing task. When standing upright in quiet stance, the posture control system’s task is to keep the body’s center of gravity (CoG) above the base of support, and the variables controlled for this are the horizontal coordinates of the CoG [17]. Thus, the horizontal plane is the postural task’s reference plane (Figure 1). Our mental navigation task, a variant of the Brooks spatial matrix task [18], involved covertly moving an object on a grid to the instructions ‘right’, ‘left’, ‘forward’, ‘back’ in the aligned orientation condition (Figure 1A), or ‘right’, ‘left’, ‘up’, ‘down’ in the non-aligned condition (Figure 1B). Thus, the task frame in the aligned condition was aligned to the postural task’s frame in both the anteroposterior (AP) and mediolateral (ML) directions. The non-aligned condition broke alignment in the AP direction only (‘up’ and ‘down’ were orthogonal to ‘forward’ and ‘back’, whereas ‘left’ and ‘right’ were identical and had the same meaning in both conditions).

As older adults accrue deficits in postural control [19] and action and spatial imagery [20,21], and they are also more prone to posture-cognition interactions [2], we predicted that their AP postural control would be negatively affected when performing mental navigation in the non-aligned reference frame compared to performing the navigation task in the aligned reference plane. If the alignment of spatial reference frames is a separate source of posture-cognition interaction in covert spatial tasks, we expected to observe the postural cost of non-alignment even in the absence of a task performance differences between the alignment conditions. Furthermore, we predicted that any impact of the mental navigation task on postural control would be greater when the postural task is more demanding, as when the base of support is reduced by standing in closed stance.

2. Method

2.1. Participants

Fifty participants were recruited across two age groups: Younger (20-35 years) and Older (59-88 years) adults. The demographic details are summarised in Table 1 along with participants’ scores on standardized tests of cognitive functioning, which were typical for the two age groups (higher digit span and lower vocabulary score for the Younger group).

The invitation to participant panels informed the members in advance that the experiment would study balance function and was suitable only for people with no current or historical medical conditions that affected their balance. All the participants who volunteered reported a medical history free from balance problems, falling and dizziness when they attended the session. The Older participants were recruited through the Trent Ageing Panel maintained by the research group. The Younger participants were recruited from an analogous database of volunteers from the University community. All provided informed consent and received a £10 retail voucher for their participation. The study was approved Nottingham Trent University's College of Business, Law and Social Sciences Research Ethics Committee.

Insert Table 1 about here

2.2. Posture Task

Participants were asked to stand barefoot on an AMTI AccuSway force platform (Watertown, MA) in either a closed (feet flush together) or an open stance (heels 10 cm apart, feet angled comfortably) and hold a wireless computer mouse in their preferred hand. The closed stance condition reduced the area of the base of support and presented a balance challenge relative to the open stance condition. Located 1 metre in front of them was 5 x 5 grid drawn on a 70 cm x 70 cm surface placed either horizontally (at hip level) in the aligned frames condition or vertically (top of the grid at eye level) in the non-aligned frames condition (Figure 1). During all trials, participants were instructed to stand with their head level and avoid unnecessary movement. AP and ML sway data were collected via Codamotion ODIN software (Charnwood Dynamics, Rothley, UK) at a sampling rate of 50 Hz. As meta-analysis [22] has shown that velocity measures are more sensitive to differences in balance control than range-based measures, and sway velocity also better differentiates between young and older age groups, particularly in the AP direction, we adopted sway velocity as the postural performance measure.

As the cognitive task involved mental imagery, we did not include a balance-only condition because, in the absence of an assigned cognitive task, each participant would likely engage in unknown and uncontrolled imagery, undermining the condition's usual utility as a baseline for the dual-task conditions.

Insert Figure 1 about here

2.3. Spatial Imagery Task

In each trial, participants stood in the designated stance (open or closed) with their eyes closed and performed a variant of the Brookes' spatial imagery task. At the start of the trial, they were asked to imagine being located on the central square on the 5 x 5 grid. Beforehand, they had been shown a target square on the grid and given time to memorize it. During the trial, they then received a series of four movement instructions ('left', 'right', 'forward', or 'back' in the aligned frames condition, and 'left', 'right', 'up', 'down' in the non-aligned frames condition). For each instruction, they were asked to mentally move themselves one square in the stated direction. The instructions were with respect to the grid and required participants to translate but not rotate themselves. At the end of the four-step mental navigation, participants were asked to use the handheld mouse to report whether they had landed on the target square (left button) or not (right button). All paths were designed such that the last instruction determined whether the route reached the target square or not. Thus, participants needed to follow all four instructions in each trial to compete the task. They were asked to respond "as quickly as possible without sacrificing accuracy" when they heard the cue. Requiring that the response occurred after the cue ensured that the sway data in the time-period preceding the cue was not influenced by response actions of varying latency. As the cuing meant that the responses did not represent the time when the participants made their decision, we did not analyze response time. However, the instruction to respond as quickly as possible ensured that it was not feasible to re-run the sequence in memory before responding.

2.4. Procedure

In all trials, the pre-recorded auditory instructions for mental navigation were played aloud at a constant volume through two speakers placed approximately 4 m away from participants. All the instructions were recorded in natural intonation by the same female voice. Each instruction was separated by 1000 ms of silence. Each trial started with a single beep to cue participants to close their eyes. Then, a second beep cued the onset of the trial and triggered the start of postural sway recording. This was followed by a series of four instructions to represent each step of a path. The trial ended with a third and final beep, cueing the participant to click the mouse to indicate whether they had landed on the target square on the grid. Postural sway data recording ceased when a mouse button was pressed.

Participants were instructed to open their eyes once they had responded. The trial sequence was controlled by an OpenSesame [23] script that communicated in real-time with Codamotion Odin software to start and stop postural sway data acquisition.

After participating in a practice block of four trials, participants completed four experimental blocks, where stance and task grid orientation were manipulated. Within each block, the target square would remain the same for four trials, each with different routes. Block order was counterbalanced across participants, with trials specifying the order of routes randomised within each block.

Before the onset of each block, participants were given the opportunity to rest, sitting down if they wished. No time constraints were set on rests. When they indicated that they were ready to proceed, they were told which stance to stand in. After every four trials, the visual placeholder denoting the target square was moved to a new location, and it was pointed out to the participant that the target square had changed location. They were then given up to thirty seconds to reacquaint themselves with the layout of the grid and to memorise the new location of the target square.

As the experimental trials did not mechanically or visually perturb the participants' balance, and the participants had been screened in advance for pre-existing conditions, we did not apply any physical restraints such as harnesses. However, the protocol enabled the participants to take breaks between short blocks of trials, and the experimenter confirmed that they were ready to continue before proceeding with the next set of trials. None of the participants reported any discomfort or dizziness during their session.

3. Results

Prior to analysis, trials containing outliers were excluded if they contained RT values for the mental navigation task that were further than 2.5 *SD* from the mean of the participants. Then, trials were excluded where the recorded AP or ML sway velocity was more than 2.5 *SD* away from the mean. By this process, a total of 204 trials were excluded from the initial 3200 trials, 101 trials due to RT outliers, and a further 103 trials due to sway velocity outliers[1].

For each of the dependent measures of mental navigation accuracy and RT and AP and ML sway velocity, a 2(age: Younger, Older) x 2(stance: open, closed) x 2(Task frame orientation: aligned, non-aligned) mixed ANOVA was conducted with stance and task frame orientation as within-subjects factors and age as a between-subjects factor. The significance level was set at $p < .05$, and Tukey HSD tests were performed as post hoc comparisons. Generalized eta squared values are given for effect sizes.

3.1 Spatial Imagery Task

For accuracy, there was a significant main effect of age ($F(1,48) = 7.19$, $p = .01$, $\eta_G^2 = .064$). The Older group had lower accuracy. There were no other significant effects. For response time, in all task conditions, the numerical trend showed longer response times for the Older group, but there were no significant effects of age, stance or task orientation. Thus, task performance was not affected by the within-subject manipulations of stance and task orientation.

[1] There was no difference in which statistical tests were significant when the outliers were retained.

3.2 Postural Sway

3.2.1 AP sway velocity

There was a significant main effect of stance ($F(1,48) = 93.6$, $p < .001$, $\eta_G^2 = .297$); AP sway velocity was greater in closed stance. The main effects of age ($F(1,48) = 2.05$, $p = .158$, $\eta_G^2 = .03$) and task frame orientation ($F(1,48) = 1.87$, $p = .178$, $\eta_G^2 = .002$) were both non-significant. There were also significant two-way interactions between stance and age ($F(1,48) = 7.22$, $p = .01$, $\eta_G^2 = .032$), stance and task frame orientation ($F(1,48) = 7.23$, $p = .01$, $\eta_G^2 = .003$), and age and task frame orientation ($F(1,48) = 5.18$, $p = .027$, $\eta_G^2 = .004$). The three-way interaction between stance, age and task frame orientation was also significant ($F(1,48) = 5.88$, $p = .019$, $\eta_G^2 = 003$). The power of the experiment for this F value was 0.66. Figure 2 shows that, when standing in closed stance, Older participants' AP sway velocity was significantly greater than Younger participants' when performing the mental navigation task in the non-aligned than in the aligned frame orientation. Younger participants' AP sway velocity did not change as a function of task frame orientation in either stance.

Insert Figure 2 about here

3.2.2 ML sway velocity

There were significant main effects of age (F(1,48) = 7.5, p = .009, η_G^2 = .115) and stance (F(1,48) = 27.06, p < .001, η_G^2 = .044), but not of task frame orientation (F(1,48) = .15, p = .701, η_G^2 < .001). None of the interactions was significant.

Figure 3 shows that ML sway velocity was greater in the Older participants in both stances, and greater for both age groups in the closed stance. There was a numerical mean difference suggesting higher ML sway velocity of the Older age group when performing the mental navigation task in the non-aligned relative to the aligned frame orientation in the closed stance condition. In the absence of significant effects involving task frame orientation, we did not interpret this difference.

Insert Figure 3 about here

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4. Discussion

The reported experiment tested the effects on postural sway of performing a non-visual spatial cognitive task in an aligned or non-aligned reference frame. In maintaining quiet stance, the variable controlled by the posture control system is the horizontal position of the CoG [17]. The mental navigation task had its operations defined either in the horizontal plane (so that the reference planes for the task and posture control were parallel and aligned), or in the vertical plane (so that the reference planes were orthogonal and non-aligned in the AP axis).

As expected from the literature on the decline in spatial cognition with ageing [21], the Older group's mental navigation task accuracy was lower. Aging has a negative effect on spatial imagery [24, 25], particularly in activating and manipulating spatial representations [26]. Age-related deficits also occur in navigation tasks [27-29] and are more prominent in novel than familiar contexts [30]. This implicates route-learning, planning and integration operations as the deficit sources [31]. Here, there was a main effect of age, but the age groups did not differ in their ability to perform the mental navigation task in the two spatial orientations. Thus, the postural performance differences due to task frame orientation could not be attributed to differences in task difficulty or load.

With respect to postural sway, higher velocity was expected in the Older group [22]. This was confirmed by significant main effects of age in both AP and ML components. For both AP and ML, significant main effects of stance (higher sway velocity in closed stance) confirmed that balancing was more challenging in closed stance. Then, the key result occurred in the closed stance condition, where the Older group's AP sway velocity was higher when mentally navigating in the non-aligned than the aligned frames condition (Figure 2). A similar numerical trend was visible for ML sway velocity (Figure 3) but there was no statistically significant effect of task frame orientation. Therefore, we concluded that the negative impact of performing the mental navigation task in a non-aligned reference plane was confined to the challenging stance and the dimension of non-alignment. This result implicates the overhead of performing the postural and spatial cognitive tasks in non-aligned reference frames.

This experiment showed that performing a spatial mental task in a reference frame that is not aligned to that of posture control affected the Older participants' sway in the direction of mis-alignment when the balancing task was more challenging. However, there are several aspects of interest that this study did not address. First, we did not test participants for differences in spatial cognitive function or imagery ability or vividness. Future studies should investigate the effects of these differences on the observed postural effects. Second, the movement instructions in the navigation task were with respect to the task grid, not with respect to the changing orientation of the object moving over the grid. In everyday mental navigation tasks, the egocentric orientation changes relative to other objects in the environment. For example, turning left or right changes which objects appear to the left or right of the locomoting person, and which direction is faced following further turns. Navigating with egocentric orientation changes is potentially a more demanding task. So, the effects of reference frame alignment under those conditions would be valuable to research. Third, the present design left open the possibility that the frame-alignment manipulation affected postural sway by producing a shift in task prioritization. The observed effect on posture control occurred in the context of clear instructions in all condition to give equal priority to both tasks. As such, a change in task prioritization is an indication of the cognitive task's requirements impinging on the resourcing of the postural task. Future studies could manipulate task prioritization to investigate this possibility further.

According to Maylor and Wing's [8] hypothesis, Brooks-type spatial memory tasks that invoke the visuo-spatial sketchpad (VSSP) amplify age-related differences in postural stability. They suggested that this is because "setting up and manipulating internal visuo-spatial information (use of the VSSP) reduces the ability to use external visual information in the control of postural sway (P152)." This hypothesis may be consistent with the results Fraizer and Mitra [15] obtained with visual search as the cognitive task. As the present results were obtained under eyes-closed conditions, impeding the utilization of visual information is unlikely to be the reason why invoking the VSSP affects posture control. The present results do clarify, however, that *setting up* internal visuo-spatial information in a reference frame that is not aligned with the postural task's frame can be a source of interference separately from the load of *manipulating* that information. Aside from overtly spatial tasks like mental navigation, a range of apparently non-spatial cognitive tasks is thought to make use of spatial imagery. For example, the commonly used backward digit recall task appears to involve a spatial representation of the digit sequence to facilitate recall in reverse order [32]. Such strategies involve setting up a spatial context or reference frame for the required operations. As postural control must continue in its gravity-determined reference frame, dual-task costs may arise from limitations in the capacity to maintain and operate within multiple spatial contexts. Alternatively, dual-task cost may arise from the additional load of tracking transformations between these contexts to avoid disorientation. Thus, there may be functional linkages [13] between spatial cognitive tasks and postural control even when the tasks are not placing separate and potentially conflicting demands on the visual system. As spatial imagery is a common and frequent cognitive task, further research could investigate the extent to which training might improve the ability to manage its spatial context alongside that of postural control.

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Figure Captions

Figure 1. Relationships between the reference planes of the postural and mental navigation tasks. In the aligned reference planes condition (A), the (mental) navigation occurred on a horizontal grid with the directional instructions “left”, “right”, “forward” and “back”. The postural task involved controlling the AP and ML coordinates of the body’s center of gravity. The reference planes of the two tasks were therefore parallel and aligned in both dimensions. In the non-aligned reference planes condition (B), the navigation occurred on a vertical grid with the instructions “left”, “right”, “up” and “down”. Here, the task’s reference plane was orthogonal to that of the postural control task, and non-aligned in postural control’s AP direction. A and B show closed and open stance, respectively. Both tasks were performed standing in both stances without vision.

Figure 2. AP sway velocity of Younger and Older groups standing in open and closed stance and performing the mental navigation task in aligned and non-aligned reference plane conditions. In the closed stance, the Older group had higher AP sway velocity when performing the mental navigation task in the non-aligned reference plane condition. The main effect of stance was also significant (AP sway of both groups was lower in open stance in both alignment conditions). The significant post-hoc mean comparisons for closed stance are shown as **(p<.01) and ***(p<.001).

Figure 3. ML sway velocity of Younger and Older groups standing in open and closed stance and performing the mental navigation task in aligned and non-aligned reference plane conditions. The main effects of age and stance were significant. The significant

post-hoc mean differences between Younger and Older are shown as * (p<.05), **(p<.01).