The interplay between posture control and memory for spatial locations

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Abstract Three experiments examined interactions between posture control in upright stance and a concurrent location memory task. Healthy young participants stood upright and memorized the locations of dots presented on a computer screen. In the retrieval phase, they indicated whether arrows presented on the screen would pass through any of the memorized locations. Postural sway variability was measured either during the retention period or during retrieval. Relative to not performing the memory task, postural sway variability increased in the retention period when the eyes were closed, but remained unaffected when the eyes were open. During retrieval, postural sway variability was reduced relative to the no-memory-task condition. Results were interpreted in terms of dual-task costs associated with maintaining multiple frames of reference.

Keywords Spatial memory · Posture control · Reference frames · Dual-tasking

Introduction

Despite the apparent effortlessness of motor coordination in the well-functioning adult, motor processes involved in everyday tasks such as walking or standing are known to interact in intricate ways with a variety of concurrent cognitive tasks (Fraizer and Mitra 2008a; Li and Lindenberger 2002; Woollacott and Shumway-Cook 2002). Cognitive distracter tasks, particularly (but not exclusively) those involving spatial operations, can increase postural sway during unperturbed stance, delay post-perturbation recovery, or induce loss of balance in extreme conditions, especially in older adults and balance-impaired patients (Barra et al. 2006; Maylor and Wing 1996; Vander Velde et al. 2005). This interference is usually interpreted as the result of competition for capacity-limited information-processing resources shared by cognitive tasks and postural control (Woollacott and Shumway-Cook 2002).

In the case of spatial tasks, Maylor and Wing (1996) proposed, for example, that layering a spatial task over ongoing postural control actions could skirt capacity limits in the visuospatial sketchpad component of working memory. Another proposal is that configurational incompatibilities between concurrent spatial tasks (e.g., non-aligned reference frames) may generate performance costs by requiring task-spaces that are kept in register to avoid disorientation. Fraizer and Mitra (2008b) have recently shown that standing upright and visually searching for a target presented in a reference frame anchored to the swaying body increased postural sway variability relative to searching for the same target presented in the posture control system's earth-fixed reference frame. This interference occurred even when the placement of search items spanning the two reference frames controlled for the equivalence of optic flow available to guide stance control.

Fraizer and Mitra's (2008b) demonstration of the impact of non-coincident reference frames was in the context of a

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perceptual task, but non-perceptual spatial tasks such as mental navigation or location memory also have reference frames associated with them. A location memory task requiring retention of the location coordinates of a set of objects may also require a memory representation of the reference frame with respect to which the coordinates are encoded. For instance, the outline of a notice board needs to be retained for the locations of particular notices on it to be held in memory. Alternatively, the reference frame may remain visually available, requiring only item coordinates with respect to it to be retained (e.g., holding old furniture locations in memory while trying out a new room arrangement). Furthermore, when memorized locations are retrieved and reported with respect to a perceptually provided reference frame, a co-registration of reference frames across memory and perception may become part of the task requirement.

In the present study, we tested the effects of these aspects of location memory tasks on postural control during unperturbed upright stance. The task of standing upright is characterized by spontaneous body sway shaped by peripheral and central motor adjustments based on vestibular, proprioceptive, and visual detection of the body's orientation relative to the direction of balance (Paulus et al. 1989). As the direction of balance for a static participant standing on level ground is primarily constrained by the line of gravity (Roberts 1995), we interpreted stance maintenance as a spatial task in an earth-fixed reference frame (the world frame) with one axis parallel to the line of gravity.

When a standing observer memorizes a set of object locations presented in a static environmental frame, such as a computer monitor (e.g., in Fig. 1a), the reference frame the observer is most likely to use for the memory task is the frame of the monitor itself. Kunde and Hoffmann (2005) found, for instance, that the tendency to localize visual targets with respect to a given reference frame increases as the uncertainty of their locations with respect to that frame decreases. The standing observer would carry out location encoding from a viewpoint that is in motion due to postural sway, which would decrease the certainty of locations relative to any (moving) egocentric frame. If the objects on the monitor do not move relative to each other or the monitor frame, then the certainty of location coding would be highest in an allocentric reference frame such as the one defined by the monitor's edges.¹

¹ More generally, the spatial cognition literature suggests that enduring representations of locations of environmental objects use intrinsic (i.e., allocentric) reference frames (Rump and McNamara 2007). Neggers et al. (2006) suggest that this may be because egocentric encoding is essentially a parietal cortical process invoked in the context of goal-directed action, whereas allocentric coding is used by the ventral visual processing stream in the context of location judgment tasks (such as the one used in the present study).

Fig. 1 Experimental apparatus and basic procedure. **a** Participants stood on the force platform, which, in conjunction with the computer, measured postural sway. Participants faced a monitor that stood at eye height and displayed the location memory task stimuli. **b** Depiction of the stimuli during the different task phases (encoding, retention, and retrieval) for Experiments 1 and 2. During the encoding phases, three (easy) or six (difficult, as depicted here) dots appeared in random locations. During retention, the dots were removed and participants had to remember their locations while postural sway was measured. During the retrieval stage (after postural sway measurement ended), the dots were not displayed but are depicted here for illustrative purposes. An arrow (or sequence of arrows in Experiment 3) appeared on the screen and participants had to indicate whether it pointed toward the location of any of the previously displayed dots. For this schematized trial, the correct cognitive response would have been “no”. **c** Depiction of the stimuli during the different task phases for Experiment 3. During the encoding phase, dots were presented as in Experiments 1 and 2. During the retrieval phase, participants stood with their eyes open and viewed a sequence of arrows that appeared on the screen while postural sway data were recorded. They had to identify which arrows pointed toward the location of a previously displayed dot. During the response phase, participants verbally indicated with sequential “yes” or “no” verbal responses whether each of the arrows pointed toward a dot location or not

Thus, the observer in Fig. 1 would track postural dynamics in the world frame while encoding and retaining object locations relative to the monitor's edges. In Experiment 1, we asked participants to retain locations of objects shown on the monitor while standing without vision. In the absence of vision, participants had to maintain the location coordinates with respect to a memory representation of the

task's reference frame (i.e., the display monitor). In Experiment 2, we asked participants to perform the same task, but with the reference frame of the display screen remaining visible (but blank) during the retention period. In this case, participants retained and rehearsed item locations with respect to the visible reference frame of the monitor, and so did not need a memory representation of it to carry out the task. In Experiment 3, we tested the behavior of posture control during memory retrieval, while participants' memory of the location coordinates was tested in a location-matching task. In all cases, we compared participants' postural sway during the location memory task against their sway in an equivalent no cognitive task condition.

If competition for spatial information-processing resources primarily governed the interaction between posture control and this location memory task, we expected a similar pattern of results in each experiment—adding the location memory task would generate interference resulting in greater postural sway, which we interpret here as indicating a decrease in postural stability (although this is not universally true; see, e.g., Riley and Turvey 2002). If, however, the relationship between the tasks' reference frames was the primary influence (the frame co-registration cost hypothesis), we predicted differing effects across the experiments. Where location coordinates had to be retained with respect to a memory representation of the reference frame (which gradually became non-coincident with the postural task's world frame in the absence of vision), we predicted an increase in postural sway due to the cost of remaining oriented with respect to non-coincident reference frames (Experiment 1). Where the task's reference frame remained visually available (and coincident with posture control's world frame), we predicted reduced or no significant impact on postural sway (Experiment 2). In Experiment 3, when location coordinates held in memory were being visually compared with probes presented in the monitor frame (coincident with posture control's world frame), we predicted a possible attenuation of sway to help align the memorized locations with the test frame.

Experiment 1

Materials and methods

Participants

Twenty University of Cincinnati undergraduates (10 women, 10 men; mean age = 19.21 years, age range = 18–21 years; mean height = 164.34 cm, height range = 155–196 cm) participated as a means of fulfilling a course requirement. All participants had normal or corrected-to-normal vision and had no injuries or disorders affecting balance or movement.

Apparatus

A Bertec 4060-NC force platform and Bertec AM-6701 charge amplifier (Bertec Corporation, Columbus, OH, USA) were used to measure postural activity via a PC running *Datapac 2000* software (Run Technologies, Inc., Mission Viejo, CA, USA). The force platform measured forces applied to its surface by the feet and converted these into a trajectory of the center of pressure (COP), roughly the average location of the ground reaction force vector. Example COP trajectories are shown in Fig. 2. As described below, in the present study, we employed a measure of COP variability as an indicator of posture control activity, because we evaluated hypotheses framed in terms of postural sway variability. The force platform system implemented a low-pass, anti-aliasing hardware filter with a cut-off frequency of 500 Hz. Data were sampled at 100 Hz. A 36.8 cm × 25.4 cm LCD monitor (resolution 1,024 × 768 pixels) was positioned at eye height in front of the participant at a distance of 75 cm from the front edge of the force platform. Microsoft *PowerPoint* was used to display the cognitive task stimuli on the monitor.

Procedure

Experimental procedures were approved by the University of Cincinnati Institutional Review Board. All participants signed an informed consent document. Participants stood on the force platform under blocked and counterbalanced instruction conditions of explicitly minimizing postural sway (i.e., standing as still as possible) or standing relaxed. In both conditions, participants were asked to avoid large movements, keep their arms at their sides, and look straight ahead at the computer monitor that was used for the cognitive task. Participants stood with their feet shoulder-width apart or pressed together (randomized within blocks) in order to achieve conditions of varying postural challenge, with the feet-together condition being the more challenging because it reduced the postural base of support in the mediolateral (ML) plane of motion.

Three cognitive task conditions (no task, easy task, and difficult task) were presented in random order. A total of 36 trials (3 trials per condition) were performed. The cognitive task consisted of three phases (see Fig. 1). During the initial phase, which lasted 10 s, either three (easy task) or six (difficult task) dark gray dots (2 cm in diameter) appeared in a pseudo-random location against a light gray background. Participants were instructed to concentrate on remembering the locations of the dots. The second phase began when the dots disappeared and consisted of 20 s of postural sway measurement during which participants were instructed to close their eyes and visualize the dot locations. The third phase began after posture control data collection

Fig. 2 Example stabilograms (*left*), plots of AP (anterior–posterior, i.e., forward–backward) vs. ML (medio-lateral, i.e., side-to-side) center of pressure (COP) trajectories recorded using the force platform, and the corresponding ML and AP COP time series (*right*). The COP, a commonly used index of postural sway, fluctuates irregularly over time, yielding variable profiles such as these. The *data* depicted are from Experiment 3, when the participants stood with the feet together

while performing a difficult version of the cognitive task employed in that experiment (**a**) or while not performing any explicit cognitive task (**b**). As described in the Experiment 3 results section, participants exhibited reduced postural sway variability while performing the cognitive task compared to when not performing it. This finding can be appreciated in the stabilograms and time series depicted here

ceased, at which point participants were instructed to open their eyes. At that time, a single arrow appeared on the screen. Participants were instructed to “mentally extend the arrow” and report whether or not the arrow pointed to the location of any of the previously displayed dots. The arrow was pointed toward a previously displayed dot’s location in half of the trials (any such arrow pointed directly at the center of the dot it would have intersected).

Cognitive task performance was measured as the percentage of correct responses. Three trials in each of three cognitive task conditions (no task, easy task, and difficult task) were presented in randomized order.

In the no-task condition, the dots were displayed, but participants were not instructed to memorize the dot locations, and there was no retrieval phase. They simply stood under either the relaxed or still instruction.

Results and discussion

COP variability

Postural activity was operationalized by the local standard deviation (within-trial mean of standard deviations computed over non-overlapping, 1 s windows; McNevin and Wulf 2002; Mitra and Fraizer 2004; Riley et al. 1999) of

the COP in both the ML and anteroposterior (AP) directions of postural sway. Higher values of this measure are interpreted to indicate reduced postural stability (i.e., poorer balance performance). This measure was selected because it is not biased by slow drift (non-stationarity) or a sudden change in level of the time series, as would be a measure such as the overall standard deviation of the COP time series. Repeated-measures analysis of variance (ANOVA) with factors of stance (feet-together vs. feet-apart configurations), instruction (stand still vs. stand relaxed), and cognitive task (no task vs. easy task vs. difficult task) was performed separately for local standard deviation of the ML and AP COP.

As expected, participants exhibited greater local COP variability in both the ML [$F(1, 17) = 69.63, p < .001$] and AP [$F(1, 17) = 45.77, p < .001$] directions with the feet together (ML: 0.233 cm; AP: 0.303 cm) than with the feet apart (ML: 0.172 cm; AP: 0.116 cm). As shown in Fig. 3, local COP variability in both directions was also significantly affected by the cognitive task condition [ML: $F(2, 34) = 3.60, p < .05$; AP: $F(2, 34) = 4.18, p < .05$]. Post hoc Bonferroni-Dunn comparisons revealed a significant increase in ML local standard deviation relative to the no-task control condition (0.195 cm) for the difficult (0.21 cm; $p < .05$) and easy (0.203 cm; $p < .05$) cognitive tasks and a

Fig. 3 Effects of cognitive task difficulty for ML (*top*) and AP (*bottom*) local COP standard deviation (postural sway variability) in Experiment 1. Error bars indicate one standard error

significant increase ($p < .01$) in AP local standard deviation for the difficult cognitive task condition (0.213 cm) relative to the no-task control condition (0.202 cm). No other effects were significant.

Cognitive performance

Repeated-measures ANOVA on memory task performance data found only an effect of task difficulty, $F(1, 19) = 19.20$, $p < .05$. The overall performance rates for the easy and difficult conditions, respectively, were 78 and 66% correct. Neither stance nor instruction significantly impacted cognitive performance.

Performance during the retention phase of the location memory task had a negative effect on posture control. Relative to the no-task condition, significantly higher levels of ML and AP postural sway variability were observed during the retention phase of the location memory task. In addition, cognitive performance suffered in the retrieval phase in the more difficult task condition (when a greater number of dot locations had to be remembered). These results are consistent with our hypothesis that non-coincidence of task reference frames adds cost to posture-cognition dual-tasking. They are, however, also consistent with the resource competition hypothesis (postural sway variability increased with added cognitive load), although, according to this view, postural task difficulty (standing with the feet apart in an open stance vs. with the feet together in a closed stance) would have been expected to interact with the addition of the location memory task, which was not the case here.

Experiment 2

In Experiment 1, retention of locations in memory was examined during standing with eyes closed. Since the locations to be retained were with respect to the frame of the monitor on which they were presented, a body-anchored representation of this frame was required to rehearse memorized locations while standing without vision. Experiment 2 allowed participants to keep their eyes open during the retention phase of the location memory task. In this case, the reference frame with respect to which locations had to be retained remained visually available and in alignment with the world frame of the posture control task. Thus, the potential for resource competition between the two tasks remained, predicting interference, whereas the frame co-registration cost hypothesis no longer predicted a clash between the two tasks.

Method

Participants

Twenty-four undergraduates at the University of Cincinnati (13 women, 11 men; mean age = 20.63 years, age range = 18–44 years; mean height = 168.31 cm, height range = 154.94–187.96 cm) participated to fulfill a course requirement. All participants had normal vision and had no injuries or disorders affecting balance or movement.

Apparatus and procedure

The apparatus was exactly the same as in Experiment 1, as was the procedure, except that participants did not close their eyes during the second phase of the cognitive task when they visualized the dot locations presented during the first phase. Instead, they stood with their eyes open and observed the computer monitor (with a blank screen) during the 20-s period of postural sway measurement. In the no-task condition, as in Experiment 1, participants did not have to retain and rehearse dot locations in memory.

Results and discussion

Postural sway

A repeated-measures ANOVA with factors of stance (feet-together vs. feet-apart configurations), instruction (stand still vs. stand relaxed), and cognitive task (no task vs. easy task vs. difficult task) was performed separately for local standard deviation of the ML and AP COP. There was no significant effect of the cognitive task on postural sway. For AP sway, local COP variability was 0.161, 0.162, and 0.162 cm for the no-task, easy task, and difficult task

conditions, respectively, and for ML sway, local COP variability was 0.089, 0.089, and 0.088 cm, respectively.

Participants exhibited lower local COP variability when instructed to stand still than when instructed to stand relaxed [ML: 0.12 cm vs. 0.13 cm, $F(1, 23) = 10.02$, $p < .01$; AP: 0.15 cm vs. 0.18 cm, $F(1, 23) = 6.74$, $p < .05$]. Also, participants exhibited greater local COP variability in the ML direction only when standing with their feet together (0.16 cm) than apart (0.09 cm), $F(1, 23) = 167.90$, $p < .001$.

Cognitive performance

Repeated-measures ANOVA on cognitive performance data revealed no significant effects—there were no effects of stance, instruction, or task difficulty on memory performance. The overall performance rates were 68% correct for the easy task and 63% for the hard task.

Unlike in Experiment 1, the location memory task's reference frame in this experiment was visually available to participants during the retention phase. Also, the memory task's reference frame (the visible monitor's edges) and the postural task's world frame were coincident. In contrast to the results of Experiment 1, the location memory task did not result in an increase in postural sway (relative to not performing a secondary task) in this experiment. This result is consistent with the frame co-registration cost hypothesis, but not with resource competition, which predicted interference between concurrent spatial tasks.

Experiment 3

Experiments 1 and 2 focused on the interaction between posture control and the retention phase of the location memory task. Relative to the no-task condition, postural sway variability increased in the non-aligned frames dual-task condition (Experiment 1), but was unaffected in the aligned frames condition (Experiment 2). This combination of results supported the hypothesis that posture-cognition dual-task performance is sensitive to the alignment between the tasks' reference frames, but did not support the expectation of persistent interference due to resource competition. Experiment 3 studied the effect of reference frame alignment in the retrieval phase of the location memory task. The retrieval task was the same as in Experiments 1 and 2—participants were asked to indicate whether arrows presented on the monitor screen, if extended, would pass through one of the memorized dot locations (Fig. 2).

Unlike in Experiments 1 and 2, however, postural sway in this experiment was measured while participants matched dot locations held in memory with arrow directions presented visually. The frame co-registration

hypothesis predicted that reducing sway during this phase of the task would help map the location coordinates held in memory to the visual coordinates of the arrows on the screen. An identical prediction is offered by the functional integration hypothesis of Stoffregen et al. (2007), which is based on the idea that postural control is adaptively modulated by the demands of non-postural tasks. Reducing the amount or variability of postural sway can facilitate performance of precision visual tasks that require ocular stability, for example. In contrast to those perspectives, the resource competition hypothesis again predicted that the conjunction of two spatial tasks would produce interference—relative to not retrieving locations from memory, doing so would result in greater levels of sway.

Method

Participants

Twenty University of Cincinnati undergraduates (10 women, 10 men; mean age = 20.3 years, age range = 18–28 years; mean height = 164.47 cm, height range = 157.48–198.12 cm) participated as a means of fulfilling a course requirement. Participants had no injuries or disorders affecting balance or movement and had normal or corrected-to-normal vision.

Apparatus

The apparatus used was the same as in Experiments 1 and 2, except for slight modifications to the cognitive task stimuli described in the “Procedure”.

Procedure

As in Experiments 1 and 2, participants stood on the force platform under blocked and counterbalanced instruction conditions of explicitly minimizing postural sway or standing relaxed. In both conditions, participants were again asked to avoid large movements, keep their arms at their sides, and look straight ahead at a computer monitor that was used for the cognitive task. Participants stood with their feet shoulder-width apart or pressed together (randomized within blocks). Three cognitive task conditions (no task, easy task, and difficult task) were presented in random order. A total of 36 trials (3 trials per condition) were performed. The cognitive task consisted of three phases. Postural sway was measured only during the second stage. During the first stage, four dark gray dots, each with a diameter of 2 cm, were presented for 10 s on a light gray background. Participants were instructed to concentrate on remembering the locations of the dots. The second phase consisted of 20 s of postural sway measurement that began

after the dots disappeared. During that 20-s span, four arrows (6 cm long) were presented sequentially on the monitor, each arrow appearing on the screen for 5 s. As in Experiments 1 and 2, participants were instructed to “mentally extend” the arrows in the direction they were pointing and decide which arrows would contact the previously displayed dots. A random percentage of arrows pointed toward the previously displayed dots’ locations in each trial (all such arrows pointed directly at the center of any dots they would have intersected). In the easy condition, any arrow that would be considered a “hit” had the point of the arrow placed directly adjacent to the locations at which the dots were previously displayed, whereas in the difficult condition, the arrows’ points were 6 cm (one arrow length away) from the dot locations. The third stage began after postural sway data collection ceased, at which point participants were asked to indicate which arrows would have intersected the dots by expressing four successive yes–no verbal responses. The no-task condition followed the same pattern except that participants did not have to remember and match dot locations in the second phase or report in the third phase. Cognitive performance was measured as the percentage of correct responses per trial.

Results and discussion

COP variability

Repeated-measures ANOVAs with factors of stance (feet-together vs. feet-apart configurations), instruction (stand still vs. stand relaxed), and cognitive task (no task vs. easy task vs. difficult task) were performed. Local COP variability was greater with the feet together than with the feet apart [ML: $F(1, 19) = 101.96$, $p < .05$; AP: $F(1, 19) = 17.38$, $p < .05$], and local variability of the ML COP decreased as cognitive task difficulty increased, $F(2, 38) = 9.28$, $p < .05$. Both of those effects must be interpreted in light of significant stance $\times$ difficulty interactions [ML: $F(2, 38) = 3.70$, $p < .05$; AP: $F(2, 38) = 6.54$, $p < .05$], as shown in Fig. 4. Those interactions indicated for both ML and AP sway that in the feet-apart condition, there was no effect of the cognitive task (all $p > .05$), whereas in the feet-together condition, local COP variability was reduced (all $p < .005$) during cognitive performance for both easy and difficult tasks (which did not differ from each other, both $p > .05$) compared to the no-task condition. For AP sway, a significant stance $\times$ instruction interaction was present, $F(1, 19) = 4.50$, $p < .05$, which indicated no significant effect ($p > .05$) of stance in the relaxed condition (feet apart: 0.130 cm; feet together: 0.141 cm), but for the still condition, participants exhibited a significant decrease in local COP variability ($p < .0125$) with the feet apart (0.119 cm) than with the feet together (0.141 cm).

Fig. 4 Stance $\times$ cognitive task difficulty interactions for ML (top) and AP (bottom) local COP standard deviation (postural sway variability) in Experiment 3. Cognitive task difficulty did not have a significant effect on postural sway variability in the more stable feet-apart condition, but postural sway variability was reduced when performing either the easy or difficult task when standing in the less stable feet-together stance. Error bars indicate one standard error

Cognitive performance

Two participants’ cognitive performance data were lost, so analyses were performed on the data from the remaining 18 participants. Repeated-measures ANOVA on the mean cognitive performance data found only an effect of cognitive task difficulty, $F(1, 17) = 6.90$, $p < .05$. The overall performance rates for the easy and difficult conditions, respectively, were 77 and 69% correct. Neither stance nor instruction impacted cognitive performance (all other $p \geq .27$). As an alternative to this scoring scheme, we also analyzed cognitive performance as an “all or none” response (all four responses on a trial had to be correct or an error was scored), yielding a mean accuracy rate of 34%. ANOVA on those data revealed no significant effects.

There was a reduction in sway variability when participants had to perform the location retrieval and matching task while standing in the feet together stance, where postural sway is naturally greater in magnitude and is expected to be a greater detriment to matching memorized location coordinates with visually presented arrow directions. This result is consistent with the frame co-registration cost hypothesis and with the functional integration hypothesis of Stoffregen et al. 2007 (the results of Experiment 1 are not

consistent with the latter hypothesis, however), but is not consistent with the resource competition account, which predicted increased sway variability in the dual-task condition than in the no-task one.

General discussion

Across Experiments 1–3, concurrent performance of a location memory task while maintaining unperturbed upright posture was shown to increase postural sway variability (Experiment 1), have no effect on postural sway variability (Experiment 2), or decrease postural sway variability (Experiment 3) relative to the respective no-task condition in each study. In the first two experiments, postural sway variability was measured during the retention phase of the location memory task, and in the third experiment, the focus was on the retrieval phase of the task. During the retention phase, the inability to visually anchor the memory task's reference frame to a body-external, earth-fixed reference frame resulted in an increase in sway (Experiment 1). When such visual anchoring was possible (Experiment 2), having to retain locations in memory produced no measurable impact on postural sway. When locations retained in memory had to be visually matched with arrows presented on an earth-fixed reference frame (Experiment 3), postural sway was reduced relative to the no-task condition. We interpreted the results as showing that the relationship between the reference frames for postural and cognitive tasks may be a key factor in how well such task combinations can be performed.

The most commonly used explanations of dual-task effects in posture-cognition studies have adopted a resource competition framework (Woollacott and Shumway-Cook 2002). This framework appears well suited to studies on the elderly and patient populations, because the most commonly observed dual-task effect among these participants is an increase in postural sway (or another indication of postural instability) or a decline in cognitive task performance, both of which are interpreted as resulting from insufficient resource availability. However, postural instability is not always observed in dual-task conditions. Several studies have shown reduced postural sway in older adults and clinical groups (e.g., Andersson et al. 1998; Deviterne et al. 2005; Weeks et al. 2003), and there are also instances of reduced sway among older but not younger participants in dual-task conditions that particularly challenge the posture control component (e.g., Brown et al. 2002; Melzer et al. 2001; Swan et al. 2004). Resource competition theories cannot easily explain such results, nor the results obtained in Experiment 3 of the present study, because these results seem to indicate improved postural performance rather than impaired postural performance during dual-task conditions.

Making resource-based accounts of dual-task interactions more precise requires clarifying what the resources are and precisely how and why their limits are reached. One possibility is that the capacity for information storage and manipulation is limited, in which case experimental work focuses on showing effects of task load. However, these effects have not been consistent in the posture-cognition dual-task literature, where many instances of task versus no-task effects exist, but few effects of graded task difficulty (for exceptions, see Mitra 2003; Mitra and Fraizer 2004; Pellecchia 2003). A second possibility is that the conflict between tasks is configurational, in which case research focuses on the types of tasks that conflict (e.g., spatial or verbal, etc.). There is consistent evidence that spatial tasks clash with posture control. In particular, in the few cases where actual loss of balance has been studied (e.g., Barra et al. 2006), only spatial tasks appear to have such an effect. There is, of course, evidence of apparently non-spatial tasks interfering with posture control (see Fraizer and Mitra 2008a; Ramenzoni et al. 2007), but overtly non-spatial tasks (e.g., counting backwards, random number generation, digit/letter span tasks) may yet internally utilize spatial representations, so general statements about non-spatial tasks are difficult at best.

Focusing on conflicts caused by spatial tasks, one possibility is that a limited spatial processing capacity gets depleted as another spatial task is combined with posture control (itself a spatial task). In this case, again, it should be possible to detect graded difficulty effects, but these are not abundant in the literature. Another possibility is that there is a configurational incompatibility between the task-spaces of two spatial tasks and maintaining operations in both task-spaces, while remaining oriented requires these spaces to be kept in register, and this incurs a performance cost. This could be due to intrinsic limitations in operating with respect to more than one spatial reference frame at a time. If a time-sharing system is required, then delays in the operational chain are inevitable. How sensitive the two tasks are to these delays can then become significant factors in how time-sharing can be successfully implemented. Posture control is strongly governed by gravity, and therefore has a natural time scale (related to the rate of gravitational acceleration of the body's center of mass) associated with it. There is not an option to leave the detection of sway and application of required corrective actions beyond a delay tolerance governed by the inertial properties of the body under gravity. Thus, such a system can accommodate other demands in the behavioral sequence by slowing down the rate of postural updating only up to a point.

The results of Experiment 3, and to some extent the results of Experiment 2, are consistent with the functional integration approach of Stoffregen et al. (2007). The functional integration approach has been confirmed in a number

of studies investigating perceptual (Smart et al. 2004; Stoffregen et al. 1999, 2000, 2006) and motor (Balasubramaniam et al. 2000; Riley et al. 1999; Wulf et al. 2004) tasks. Although the functional integration approach can predict the absence of cognitive effects and the presence of the effects of perceptual and motor tasks, as in the Stoffregen et al. (2007) study, this approach cannot account for the findings in Experiment 1, where cognitive performance was associated with an increase in postural sway variability that has no apparent functional consequences for either cognitive or postural performance. The frame co-registration cost hypothesis, in contrast, predicts the complete pattern of results observed over Experiments 1–3.

The present study looked at an ubiquitous type of incongruence between the task-spaces of postural and cognitive tasks—the case where the cognitive task requires spatial operations in an internally maintained reference frame that may or may not be possible to perceptually keep in register with the outside world. In these situations, the memory task-space is in some body-based reference frame. Since the body itself has to be stabilized and orientated relative to gravity, and it is in constant motion, the memory task-space is both geometrically and dynamically embedded within the postural task's task-space. If there is a limit to simultaneous operations in reference frames bearing this type of relationship, this can be an important source of conflict between posture control and spatial cognition. The present data give clear indication that the coincidence of task-spaces can be an important issue in posture-cognition competition or cooperation. Further research is needed to understand exactly why non-coincident spatial reference frames produce difficulties in dual-task situations. There may be representational limitations to setting up multiple spatial reference frames, for example, or there may be operational difficulties that occur when ongoing postural events impact task-space elements in an incompatible manner (see discussion in Fraizer and Mitra 2008b). In either case, this promises to be a research problem of significant interest in our understanding of the architecture of embodied cognition.

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