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Effects of spatial and nonspatial cognitive activity on postural stability

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Is postural stability controlled automatically, or is it affected by concurrent cognitive activity? Are the effects influenced by the nature of the cognitive activity required, and do they increase in old age? To address these questions, 70 participants aged 20–79 years were asked to stand as still as possible on a force platform (postural control task) while performing (a) no cognitive task, (b) a spatial memory task, and (c) a nonspatial memory task. The memory tasks were also performed while seated as a comparison condition. Both spatial and nonspatial memory recall declined with increasing age but were unaffected by position (standing vs. seated). Postural stability declined with age; moreover, there was support for an earlier finding that age decline was greatest when performing the spatial memory task. Each recording period was split into two phases which, for the spatial and nonspatial memory tasks, corresponded to encoding and maintaining the stimuli. In comparison with no task, participants were more stable when encoding stimuli (particularly in the spatial task), but they were less stable when maintaining stimuli (particularly in the nonspatial task). The results suggest that postural stability can be affected by cognitive activity in complex ways, depending on the age of participants, the type of cognitive task (spatial vs. nonspatial), and the cognitive processing required (encoding vs. maintenance).

In this paper, we address the relatively neglected, but nevertheless important, issue of the degree to which postural control (in the present case, the ability to maintain a stable upright stance) is influenced by additional cognitive demands. Of particular interest is whether some cognitive activities are more disruptive than others, perhaps because they share specific attentional resources with the control of posture. Also, in view of the increased incidence of falls in old age (Blake *et al.*, 1988), a question of both practical and theoretical importance is the extent to which any adverse effects of cognitive activity on postural stability are greater in older than in younger adults.

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Combining cognitive and postural control tasks

There have been many investigations combining cognitive tasks with motor tasks involving arm movements such as tracking (e.g. Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986; Haggard & Cockburn, 1998; J. G. Quinn, 1994). However, less attention has been given to the performance of cognitive tasks while simultaneously carrying out motor tasks involving postural control such as standing upright or walking. This relative neglect is surprising when it is considered that such combinations occur frequently in everyday life. A possible reason for the paucity of studies in this area is that it may have been assumed that highly practised motor control tasks, such as standing upright, can be performed automatically and are therefore unlikely to share attentional resources that are required by cognitive tasks.

However, maintaining a stable upright posture is a complex process (see Downton, 1990; Hay, 1996; Hill & Vandervoort, 1996; Tang & Woollacott, 1996, for summaries). Sensory information is provided by vision, proprioception, and the vestibular system. This input is processed centrally by several areas of the brain, including the cerebellum, brainstem, basal ganglia, and sensorimotor cortex. Postural control is then effected by limb and trunk muscles that receive impulses via the spinal cord and peripheral nerves. In view of these requirements, it would seem that there is at least potential for interference between cognitive and postural control tasks.

Effects of spatial vs. nonspatial cognitive tasks

Kerr, Condon, and McDonald (1985) argued that since visual information is important in postural control, and visual spatial imagery involves the visual system, then maintaining a difficult posture should interfere with visuo-spatial memory, but not with verbal memory. Kerr *et al.* investigated this hypothesis by asking student participants to perform Brooks' (1967) spatial and nonspatial memory tasks. In the spatial version, the task was to listen to, and then repeat back, the locations of digits in an imaginary 4 × 4 grid. In the nonspatial version, the directions right, left, up, and down were replaced by the words quick, slow, good, and bad. Both tasks were performed either while sitting or while standing in the Tandem Romberg position (i.e. with the heel of the front foot directly ahead of the toes of the back foot). As predicted, the difficult standing task produced a decrement in recall scores for the spatial task but not for the nonspatial task.

Kerr *et al.* (1985) interpreted their results as evidence of specific interference from the shared use of visuo-spatial information in the spatial memory and postural control tasks. However, results from subsequent studies demonstrating interference between both spatial and nonspatial cognitive tasks and postural control are more consistent with the conclusion that such tasks compete for limited central attentional resources (e.g. LaJoie, Teasdale, Bard, & Fleury, 1996b; Marsiske, Margrett, & Allaire, 1998; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). Thus it appears that there can be interference between postural control and both spatial and nonspatial cognitive tasks, although it remains unclear whether or not they cause the same degree of interference.

The first main aim of the present study was therefore to examine in detail the consequences of performing versions of Brooks' (1967) spatial and nonspatial memory tasks while concurrently maintaining a normal stable upright stance. Importantly, we were interested in divided attention costs on *both* cognitive performance and postural stability. (Note that possible trade offs between tasks could mask divided attention costs if performance on only one of the two tasks was considered.) Moreover, two separate measures of postural stability were investigated here, namely, sway variability and sway velocity, in an attempt to determine which (if any) aspect of postural control is affected by concurrent cognitive activity.

Attentional demands of encoding, maintenance and retrieval

Episodic memory tasks, such as Brooks' (1967) spatial and nonspatial memory tasks, can be divided into three phases: encoding, maintenance (involving storage and rehearsal processes), and retrieval. Recent work by Craik and his colleagues (Anderson, Craik, & Naveh-Benjamin, 1998; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996; Naveh-Benjamin, Craik, Guez, & Dori, 1998) has compared the attentional demands of the encoding and retrieval phases by considering the effects of a secondary task, such as manual reaction time (RT), on memory performance, and vice versa. It appears that while secondary task costs are associated with both encoding and retrieval, memory performance is more adversely affected by a secondary task at encoding than at retrieval. In other words, both encoding and retrieval phases of memory tasks are attentionally demanding as indicated by impaired secondary task performance.

Encoding and maintenance phases of memory tasks have also been compared with dual task methodology. G. Quinn (1991) summarized a number of studies that examined spatial memory while performing secondary motor tasks during encoding and maintenance. Memory is more disrupted by motor interference while encoding than maintaining stimuli. However, it is not known whether encoding is more attentionally demanding than maintenance (as would be revealed by greater secondary task costs).

As a second aim of the present study, we planned to compare directly the effects of all three phases of the spatial and nonspatial memory tasks (encoding, maintenance and retrieval) on postural stability. Unfortunately, the retrieval phase posed difficulties because both verbal and written recall can physically interfere with standing balance (e.g. see Yardley, Gardner, Leadbetter, & Lavie, 1999). We therefore restricted the present study to a comparison of the effects of the encoding and maintenance phases (attending to external and internal stimuli, respectively) on postural stability. As already noted, it is not clear from the existing literature which of these two phases would cause more interference.

Dual task costs and ageing

Our third aim was to examine the effects of spatial and nonspatial cognitive activity on postural stability across adulthood on the basis that attentional resources are generally reduced by ageing (Craik & Byrd, 1982; Rabinowitz, Craik, & Ackerman, 1982; Salthouse, 1991, 1992), leading to increased divided attention costs (e.g. Anderson *et al.*, 1998). A recent study by Lindenberger, Marsiske, and Baltes (in press) examined both the speed and accuracy of walking while performing a memory task requiring mental imagery in young, middle-aged and old adults. Dual task costs for both walking and memorizing increased significantly across the three age groups, consistent with the conclusion that the cognitive demands of sensorimotor tasks increase across adulthood. There was no difference between memory performance when seated and standing in any age group. However, postural stability was not monitored so there may have been a trade off between the standing and cognitive tasks.

Both postural stability and cognitive performance were investigated in a study by Maylor and Wing (1996) in which middle-aged and elderly participants were required to stand on a force platform while performing five cognitive tasks: random digit generation, Brooks' spatial memory, backward digit recall, silent counting from 1–100, and counting backwards in threes (aloud). There was also a control condition in which there was no cognitive task. As in Lindenberger *et al.*'s (in press) study, cognitive performance was no worse when standing than when seated (with the exception of random digit generation). Postural stability was adversely affected by age in all conditions, as expected (see Anstey, Stankov, & Lord, 1993; Hay, 1996; Hill & Vandervoort, 1996; Sheldon, 1963; Tang & Woollacott, 1996; Wolfson *et al.*, 1992). However, the postural stability difference between the two age groups was significantly greater when performing the visuo-spatial tasks (i.e. Brooks' spatial memory and backward digit recall[1]), in comparison with the age difference in the control condition.

Maylor and Wing (1996) argued that setting up and manipulating internal visuo-spatial information interferes with the ability to use external visual information in the control of postural stability (cf. Kerr *et al.*, 1985). The differential effect of performing visuo-spatial tasks on younger and older adults occurs because there is significant decline in proprioceptive and vestibular information with old age. Vision can normally compensate for such impairments but not under reduced vision conditions, e.g. with the eyes closed (Downton, 1990; Teasdale, Bard, LaRue, & Fleury, 1993; Woollacott, Shumway-Cook, & Nashner, 1982) or with visuo-spatial interference from a cognitive task (Maylor & Wing, 1996). However, it should be noted that Maylor and Wing did not include nonspatial tasks that were necessarily equivalent to the spatial tasks in all respects except the nonspatial/spatial element. It is therefore possible that the interactions observed with age for spatial tasks could be attributed to some other characteristic of those particular tasks such as a high level of difficulty.

Summary of the present experiment

We directly compared the effects of spatial and nonspatial cognitive tasks on postural stability by adapting Brooks' (1967) memory tasks as described earlier. Difficulty levels were selected with the intention of producing (a) approximately equivalent levels of performance across the two memory tasks, and (b) relatively accurate performance in part to ensure that participants would be motivated to attempt the memory tasks under all conditions. Two measures of postural stability (sway velocity

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[1] Participants reported using a visuo-spatial strategy in the backward recall task. Independent evidence that backward recall involves visuo-spatial representations comes from Li and Lewandowsky (1995).

and variability) were recorded during both the encoding and maintenance phases of the memory tasks. Differences in postural stability while encoding and maintaining stimuli were assumed to indicate differences in the attentional demands of the two phases. Participants in each decade from 20-year-olds through to 70-year-olds were tested; from the ageing literature, we expected the greatest decline in cognitive and motor performance, and the greatest dual task costs, to occur between the 60s and 70s age groups (see Salthouse, 1991; Schaie, 1996). Thus the present study investigated the effects of different memory tasks (spatial vs. nonspatial) and different cognitive processes (encoding vs. maintenance) on postural stability across adulthood.

Method

Participants

The participants were 70 volunteers. They were all members of a research panel at the MRC Applied Psychology Unit, Cambridge, UK. There were either 11 or 12 participants in each of the six age decades from the 20s through to the 70s, with approximately twice as many females as males in each age group (see Table 1 for details). Participants were not recruited for the study unless: (a) they claimed to have reasonable hearing, (b) they were unaware of ever having suffered a stroke, and (c) they were able to stand unaided with ease. It was requested that comfortable flat shoes should be worn for the study. Participants each received a small honorarium and a contribution towards their travel expenses.

Table 1. Participant details

	N		Age		
Age group	Males	Females	Range	*M*	SD
20s	3	8	20–26	22.4	1.9
30s	4	8	30–39	35.7	3.4
40s	4	7	40–49	43.9	3.1
50s	4	8	50–59	53.7	3.0
60s	4	8	60–69	65.3	3.2
70s	4	8	71–79	73.5	2.9

Apparatus and stimuli

Ground reaction forces and torques, generated in maintaining standing balance, were measured with a force plate (Bertec 6080). These were used to determine the centre of pressure in both the antero-posterior and medio-lateral directions. Participants were required to stand on outline footmarks placed in the centre of the force plate such that the outer edges of their feet were 27 cm apart. They were also asked to place their feet on the outline footmarks when seated on a chair immediately behind the force plate.

The Bertec force plate was placed approximately 1.5 m in front of a large plain screen. In the centre of the screen there was a small circular hole immediately behind which was a loudspeaker. The black central circle served as the fixation point throughout the experiment.

There were two cognitive tasks, based on Brooks' (1967) spatial and nonspatial memory tasks. For each task, two different sets of stimuli were produced (sets A and B). In each set for the spatial task, there were four stimuli of length 4, four of length 5, four of length 6, and four of length 7 (a total of 16 stimuli per set). Each stimulus was a list of 4, 5, 6, or 7 instructions for placing consecutive numbers in a 4 × 4 grid (see Fig. 1a for an example). The first instruction was always 'In the starting square put a 1'. The starting square was the second row of the second column of the grid. The instructions

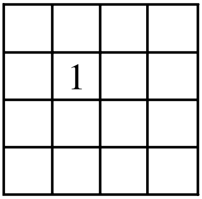
	(a) Spatial task	(b) Nonspatial task
Stimulus	In the starting square put a 1. In the next square to the right put a 2. In the next square down put a 3. In the next square to the left put a 4. In the next square to the left put a 5.	In the starting square put a 1. In the next square to the quick put a 2. In the next square to the bad put a 3. In the next square to the slow put a 4. In the next square to the slow put a 5.
Response sheet		In the starting square put a 1. In the next square to the ______ put a 2. In the next square to the ______ put a 3. In the next square to the ______ put a 4. In the next square to the ______ put a 5.

Figure 1. Examples of stimuli and response sheets for (a) the Brooks spatial task, and (b) the Brooks nonspatial task. List length = 5 in both cases.

continued: 'In the next square to the right/to the left/up/down put a 2. In the next square to the right/to the left/up/down put a 3' and so on to the end of the list (4, 5, 6, or 7 instructions). The directions (right, left, up, and down) were randomly chosen with the restrictions that a number was never placed outside the grid or in a square already occupied.

The two sets of stimuli for the nonspatial task (again, sets A and B) were derived from the spatial task stimuli by replacing the words right, left, up, and down, with the words quick, slow, good, and bad, respectively (i.e. 'In the starting square put a 1. In the next square to the quick/slow/good/bad put a 2' and so on; see Fig. 1b). However, the last instruction in each list was omitted so that there were four stimuli of length 3, four of length 4, four of length 5, and four of length 6. This was based on the results of Brooks (1967) which indicated that the nonspatial task was more difficult than the spatial task.

The spatial and nonspatial stimuli were read out by a male speaker and recorded on to audiotape. For the spatial task, each stimulus began with the word 'Ready'. Three seconds later, the first instruction began ('In the starting square…'). Each subsequent instruction was then presented exactly 3 seconds after the beginning of the previous instruction (with each instruction taking 3 seconds) so that a stimulus of length 5 took 15 seconds to present. Ten seconds after the end of the last instruction, the word 'Repeat' was presented. For the nonspatial task, the word 'Ready' again signalled the start of each stimulus followed 3 seconds later by the first instruction. Each subsequent instruction was then presented 4 rather than 3 seconds after the beginning of the previous instruction (therefore leaving a 1-second gap between instructions) so that in this case a stimulus of length 4 lasted 15 seconds (4+4+4+3). As before, the word 'Repeat' occurred 10 seconds after the end of the last instruction.

There were two response sheets, one for each task. These were attached to a clipboard so that participants could write easily while seated. For the spatial task, there were 16 grids which were empty except for the number '1' in the starting square (see Fig. 1a). For the nonspatial task, there were 16 sets of sentences with the crucial adjectives omitted ('In the starting square put a 1. In the next square to the __ put a 2' etc); see Fig. 1b.

Design and procedure

Participants were tested individually in a single 90-minute session. To summarize the study, participants were required to stand on the force plate on six separate occasions during the session without performing any concurrent cognitive task, and to perform the Brooks (1967) spatial and nonspatial memory tasks both while seated and while standing on the force plate.

The session began with the first run of the standing task performed alone. Participants were required to stand on the force plate, with their feet on the outline footmarks and their arms by their sides, and to look straight ahead at the fixation point. The instructions were to stand as still as possible. The experimenter verbally indicated the beginning and end of the recording period of 25 seconds ('Ready... Stop'). A further five runs of the standing task alone were conducted during the session as follows: once between the first and second halves of the first memory task, twice between the two memory tasks, once between the first and second halves of the second memory task, and once at the end of the session. Participants were frequently reminded throughout the experiment of the requirement to remain as steady as possible when standing.

Half of the participants in each age group performed the spatial task followed by the nonspatial task, while the remaining participants performed the memory tasks in the reverse order. Also, half of the participants in each age group received stimulus set A for the spatial task and stimulus set B for the nonspatial task, while the remaining participants received the reverse (i.e. set B for the spatial task and set A for the nonspatial task).

For the spatial task, the layout of the grid, the location of the starting square, and the general task requirements were explained to the participant using a sample grid with numbers inserted together with the corresponding series of sentences. Participants were told that they would hear similar sequences (of different lengths) and that their task was to remember them for later recall by writing the appropriate numbers on to empty grids (except for a '1' in the starting square). They were specifically directed to form a mental image of the grid, placing the numbers in the imagined squares as the sentences were presented. While the participant was seated and looking at the fixation point, four practice stimuli were presented, each of length 4. Upon the instruction 'Repeat', the experimenter produced the response sheet and a pen and asked the participant to recall the sequence by writing the numbers in the appropriate squares of the grid. Following the practice stimuli, there were four experimental runs each with three stimuli which were presented in ascending order of length (5–6–7). Participants were always informed of the list length before it was presented. Two of the four runs of three stimuli were conducted while seated and two runs were conducted while standing. For half of the participants in each age group, the order of the four runs was seated–standing–standing–seated; for the remaining half of participants, the order was standing–seated–seated–standing. (The same order applied to both the spatial and nonspatial tasks for each participant.) When standing and performing the spatial task, participants were asked to stand as still as possible between the instructions 'Ready' and 'Repeat'. In fact, balance was monitored from the onset of the first, second, or third instruction for list lengths 5, 6, or 7, respectively, until the signal to 'Repeat'. Thus balance was always recorded in periods of 25 seconds, with the first 15 seconds corresponding to encoding (i.e. listening to the instructions), and the last 10 seconds corresponding to maintenance (i.e. storing and rehearsing the instructions in preparation for recall). Participants always recalled the lists while seated.

For the nonspatial task, participants were shown an example list of sentences and were told that similar lists (of different lengths) would be presented and that their task was to remember the target adjectives for later recall by writing the words in the appropriate spaces on the response sheet. They were encouraged to use a verbal rather than a spatial strategy in encoding and maintaining the presented sequence of adjectives. The practice and experimental trials were conducted as for the spatial task except that the list lengths were shorter (length 3 for practice, and lengths 4, 5, and 6 for experimental trials). When performing the task while standing, balance was monitored from the onset of the first, second, or third instruction for list lengths 4, 5, or 6, respectively, until the signal to 'Repeat'. So, as before, the first 15 seconds of recording corresponded with encoding, and the last 10 seconds corresponded with maintenance.

Data analysis

There were two measures of postural stability: (1) average sway velocity (i.e. distance in centimetres traced by the centre of pressure per second), and (2) sway variability (i.e. SD of the centre of pressure), in the antero-posterior and medio-lateral directions separately. The former reflects the speed of change in the centre of pressure; in other words, the faster a participant sways or wobbles, the further the distance traced by their centre of pressure in unit time. The latter reflects the extent of a participant's movements; in other words, the further away a participant sways or wobbles from an upright stance, the greater the SD of the centre of pressure. Although in practice the two measures tend to be positively correlated (at approximately .53 in the present data), it is theoretically possible for them to be completely unrelated. Thus participants may move quickly and far (high velocity; large variability), slowly and not far (low velocity; small variability), quickly but not far (high velocity; small variability), and slowly but far (low velocity; large variability). Similarly, sway variability in the antero-posterior and medio-lateral directions are not necessarily related (although, again, they are correlated in the present data at approximately .69). Each measure of postural stability was calculated separately for the first 15 seconds and last 10 seconds of each 25 seconds recording period.

For the Brooks spatial task, the dependent measure was the number of digits correctly located in the grid as a proportion of the number of presented digits (not including 1, which was provided). For the Brooks nonspatial task, the dependent measure was the number of adjectives correctly recalled as a proportion of the number of presented adjectives (again, one fewer than the list length). For both the Brooks spatial and nonspatial tasks, the proportions were calculated separately for each level of difficulty (list lengths 5, 6, and 7 for the spatial task; list lengths 4, 5, and 6 for the nonspatial task).

Results

All reported effects are significant at $p < .05$ or better, unless otherwise stated.

Cognitive performance

The three versions of the Brooks spatial and nonspatial tasks were each performed twice while seated and twice while standing. A five-way analysis of variance (ANOVA) was therefore conducted on the proportion correct with age group (6 levels) as the between-participants factor, and task type (spatial vs. nonspatial), position (seated vs. standing), practice (first trial vs. second trial), and difficulty (3 levels) as within-participants factors.[2] There were significant effects of age group, $F(5,64) = 6.47$, task type, $F(1,64) = 33.51$, and difficulty, $F(2,128) = 13.16$. The effects of position ($F < 1$) and practice ($F = 1.50$) were not significant. There were interactions between age group and task type, $F(5,64) = 3.74$, between task type and difficulty, $F(2,128) = 4.70$, and among age group, task type, position, and difficulty, $F(10,128) = 2.37$.

The significant main effects and two-way interactions can all be seen in Fig. 2. Thus, performance clearly decreased with increasing age; this age decline was greater for the spatial task than for the nonspatial task. Performance was higher overall in the nonspatial task (.96) than in the spatial task (.90), and was lower at the third level of difficulty (.90) than at the first and second levels (both .95). The effect of difficulty was less marked for the spatial task than for the nonspatial task.

The four-way interaction was entirely attributable to the 70s age group in the spatial task performing worse while seated than while standing but only at the intermediate level of difficulty, for which we can offer no explanation.

To summarize the cognitive data, performance was generally accurate in both tasks although there was evidence of age decline, with the largest overall drop occurring between the 60s and 70s age groups. By using shorter list lengths for the nonspatial task than for the spatial task, we succeeded in ensuring that spatial performance was not superior to nonspatial performance (cf. Brooks, 1967). Instead, however, there was a significant (but small) advantage in favour of the nonspatial task. Increasing difficulty (i.e. list length) resulted in worse performance, but only in the nonspatial task. It should be noted that the effect of difficulty was confounded

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[2] In the analyses of variance with repeated measures, where there was evidence of departure from the sphericity assumption, the reported probability levels have been adjusted accordingly (Greenhouse–Geisser corrections).

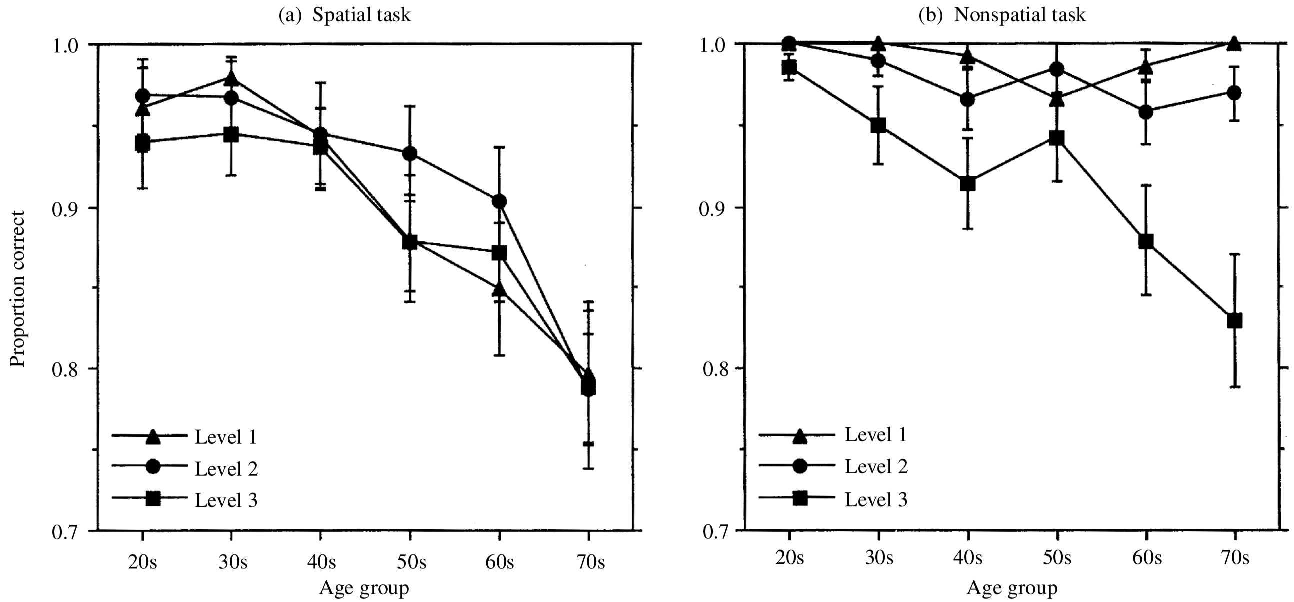

Figure 2. Mean proportion correct (± 1 SE) as a function of age group and task difficulty (3 levels) for (a) the Brooks spatial task, and (b) the Brooks nonspatial task. Levels 1–3 correspond to list lengths 5–7 (spatial task) and list lengths 4–6 (nonspatial task).

with practice (recall that the three list lengths in each condition were always administered in the same fixed order of increasing difficulty). Nevertheless, a useful feature of the data for analyses below is that spatial performance averaged across the three levels of difficulty was approximately equivalent to nonspatial performance at the most difficult level (see Fig. 2). Finally, with the exception of a single inexplicable difference, there was no influence of position on performance (.93 seated; .94 standing). The same null result was also found for three of the five cognitive tasks (including the Brooks spatial task) investigated by Maylor and Wing (1996).

Postural stability

Preliminary inspection of the postural stability data for the six runs with no cognitive task revealed no systematic differences in either sway measure over the course of the testing session. Also, analysis of the data when the spatial and nonspatial tasks were performed showed little evidence of either practice effects (from the first trial to the second trial of each condition) or difficulty effects (across the three levels of each task). Thus, in order to increase the reliability of the postural stability measures, means were calculated across the six runs from each experimental condition (no task, spatial task, and nonspatial task). Where there were missing data (either because of technical failures, or because a participant did not follow the instructions correctly), the mean was calculated over the remaining runs in that condition. In total, there were 27 missing runs out of 1260 (2.1%) which were distributed from the 20s to the 70s age groups as follows: Ns = 5, 6, 5, 5, 0, and 6.

Further inspection of the postural stability data revealed one very clear outlier (a female participant aged 31) who, according to laboratory notes, 'arrived quite flustered' and 'found it difficult to stand still'. In one condition, she was 5.0 SD away from the overall mean for the whole sample, and in another condition she was 4.0 SD away. Her data were therefore not included in the analyses reported below. Separate ANOVAs were conducted on the two measures of postural stability, namely, sway velocity and sway variability. Planned contrasts were used to compare postural stability for (a) spatial vs. no task, (b) nonspatial vs. no task, and (c) spatial vs. nonspatial tasks.

Sway velocity. Age group (6 levels: 20s–70s) was a between-participants factor, and cognitive task (3 levels: no task, spatial task, and nonspatial task), and phase (2 levels: first and second phases, corresponding to the first 15 seconds (encoding) and last 10 seconds (maintenance) of each 25-second period, respectively)[3] were within-participants factors in an ANOVA. There were significant effects of age group, $F(5,63) = 7.18$, and cognitive task, $F(2,126) = 4.24$, but no effect of phase, $F < 1$. The only significant interaction was between cognitive task and phase, $F(2,126) = 21.37$ (all other $F\text{s} < 1$).

The main effects of age group and cognitive task can be seen in Fig. 3. Clearly, the

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[3] Recall that for the spatial and nonspatial tasks, the first 15 seconds and last 10 seconds of each 25-second recording period corresponded to encoding and maintaining stimuli, respectively. The no task condition was similarly split into two phases (15 seconds and 10 seconds) to provide appropriate baselines.

70s age group (and, to a lesser extent, the 60s) changed their centre of pressure more quickly than the younger age groups resulting in a higher sway velocity, as expected. The overall means for the three experimental conditions were 1.55 (no task), 1.53 (spatial task), and 1.60 (nonspatial task) cm/s. Planned contrasts showed that, whereas the nonspatial task differed significantly from no task, the spatial task did not; the spatial and nonspatial tasks were significantly different. Figure 3 shows that the effects of cognitive task on sway velocity were similar at each age group.

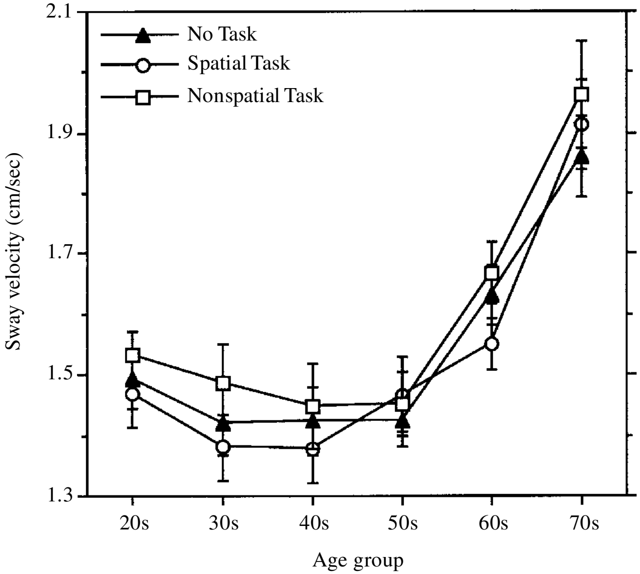

Figure 3. Mean sway velocity (± 1 SE) as a function of age group and cognitive task.

Figure 4 illustrates the significant interaction between cognitive task and phase that was apparent across all age groups. Sway velocity clearly decreased from the first to the second phase with no task, but increased from the first to the second phase with both the spatial and nonspatial tasks. For the first phase, planned contrasts revealed significant differences between no task and the spatial task, and between the spatial task and the nonspatial task, with a marginal difference between no task and the nonspatial task, $p < .06$. For the second phase, there were significant differences between all three conditions.

In considering the overall difference in sway velocity between the spatial and nonspatial tasks (see Fig. 3), which was apparent in both phases (see Fig. 4), it should be remembered that cognitive performance was slightly lower in the spatial task than in the nonspatial task (compare Fig. 2a and b). To examine the effect on sway velocity of spatial and nonspatial tasks that were equivalent in difficulty (at least in terms of proportion correct), the ANOVA was repeated using the mean of all six runs for the spatial task (two at each of levels 1, 2, and 3), but only the mean of the two runs with the longest list length (level 3) for the nonspatial task. As can be seen in Fig. 2, this

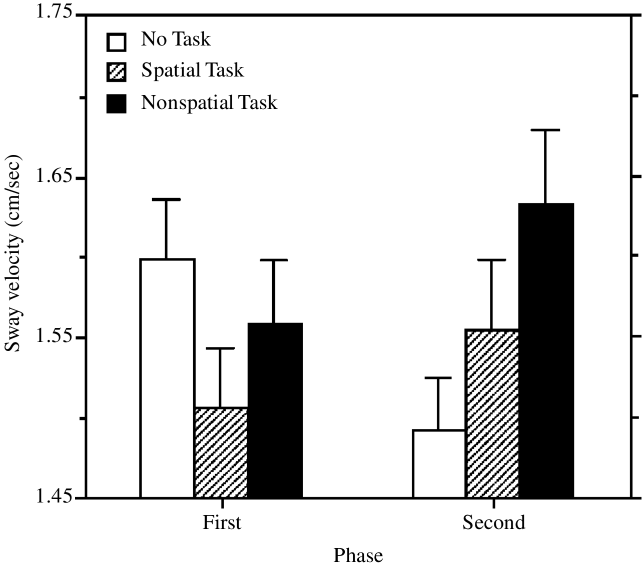

Figure 4. Mean sway velocity (+ 1 SE) as a function of cognitive task and phase. For the spatial and nonspatial tasks, the first phase (0–15 seconds) corresponds to encoding and the second phase (15–25 seconds) corresponds to maintenance.

approximately equates cognitive performance across the two Brooks tasks. The results were all as before, i.e. significant effects of age group and cognitive task, with a significant interaction between cognitive task and phase. Mean sway velocities for the nonspatial task at level 3 were 1.57 cm/s for the first phase and 1.66 cm/s for the second phase. These were slightly higher than before (cf. Fig. 4) so that the difference between no task and the nonspatial task in the first phase was no longer significant in a planned comparison. To summarize, the differences in sway velocity between the spatial and nonspatial tasks cannot be attributed to the fact that the spatial task was more difficult overall than the nonspatial task.

Sway variability. A four-way ANOVA was conducted on the second measure of postural stability, sway variability, with age group (6 levels: 20s–70s) as a between-participants factor, and cognitive task (3 levels: no task, spatial task, and nonspatial task), phase (2 levels: first and second phases), and direction (2 levels: antero-posterior and medio-lateral movements) as within-participants factors. The effect of age group approached significance, $F(5,63) = 1.97$, $p < .1$, as did the effect of cognitive task, $F(2,126) = 3.01$, $p < .06$, with overall means of 0.325, 0.330, and 0.351 cm, for no task, the spatial task, and the nonspatial task, respectively. There was no effect of phase, $F < 1$, but there was a significant effect of direction, $F(1,63) = 166.30$. There were significant interactions between age group and direction, $F(5,63) = 2.50$, between cognitive task and phase, $F(2,126) = 11.60$, and among age group, cognitive task, and direction, $F(10,126) = 2.05$ (all other Fs < 1).

Figure 5 shows sway variability averaged across the first and second phases.

Clearly participants swayed more in the antero-posterior direction than in the medio-lateral direction (compare Fig. 5a and b). The difference between the two directions was large for the 30s age group and small for the 70s age group, relative to the other age groups, hence the age group × direction interaction. There was a clear trend for an increase in sway variability with age in the medio-lateral direction, but the pattern for the antero-posterior direction was less consistent. Generally, the antero-posterior data were more variable than the medio-lateral data. Thus, in order to explore the age group × cognitive task × direction interaction, separate ANOVAs were conducted on the two directions.

For the antero-posterior direction, there was no effect of age group, $F(5,63) = 1.43$, but the effect of cognitive task approached significance, $F(2,126) = 3.06$, $p = .05$. The means were similar for no task (0.394 cm) and the spatial task (0.401 cm), and these were lower than for the nonspatial task (0.425 cm), as observed with sway velocity. The interaction between cognitive task and phase (to be discussed below) was significant, $F(2,126) = 9.49$, with all remaining F ratios < 1. Thus there was little evidence of the effect observed by Maylor and Wing (1996) with a similar measure of postural stability in the antero-posterior direction, namely, greater disruption from the spatial task in comparison with no task in old age.

The ANOVA for the medio-lateral direction revealed a significant effect of age group, $F(5,63) = 2.75$, no effect of cognitive task, $F(2,126) = 1.45$, and a marginal interaction between them, $F(10,126) = 1.83, p < .07$. Again, the interaction between cognitive task and phase was significant, $F(2,126) = 7.07$ (all other Fs < 1). In this case, the interaction between age group and cognitive task (significant on a one-tailed test) is consistent with Maylor and Wing's (1996) finding. Indeed, analysing only the data from the conditions in that study (i.e. no task and the spatial task), the age group × cognitive task interaction was significant, $F(5,63) = 2.64$. It can be seen from Fig. 5b that the difference between no task and the spatial task was considerably greater for the 70s age group (+0.119 cm) than for the 20s–60s age groups (−0.021 cm on average); although not shown, this was equally true of the first and second phases. Comparing no task with the nonspatial task, there was no significant age group × cognitive task interaction, $F < 1$, although there was a similar trend in the data such that the largest increase in sway variability from no task to the nonspatial task was for the 70s age group (see Fig. 5b). In fact, the trend was even more similar when only the data from level 3 of the nonspatial task were considered (where age decline in cognitive performance was approximately equivalent to that in the spatial task); the difference between no task and the nonspatial task (level 3) for the 70s age group was 0.114 cm compared with an average of 0.013 cm for the 20s–60s age groups.

Returning to the original four-way ANOVA on sway variability, the significant interaction between cognitive task and phase can be seen in Fig. 6. This interaction was very similar in the antero-posterior and medio-lateral directions. As in Fig. 4 for sway velocity, sway variability decreased from the first to the second phase with no task, but increased from the first to the second phase with both the spatial and nonspatial tasks. For the first phase, planned contrasts revealed that the only difference to reach significance was that between no task and the spatial task. In the second phase, there were significant differences between all three conditions.

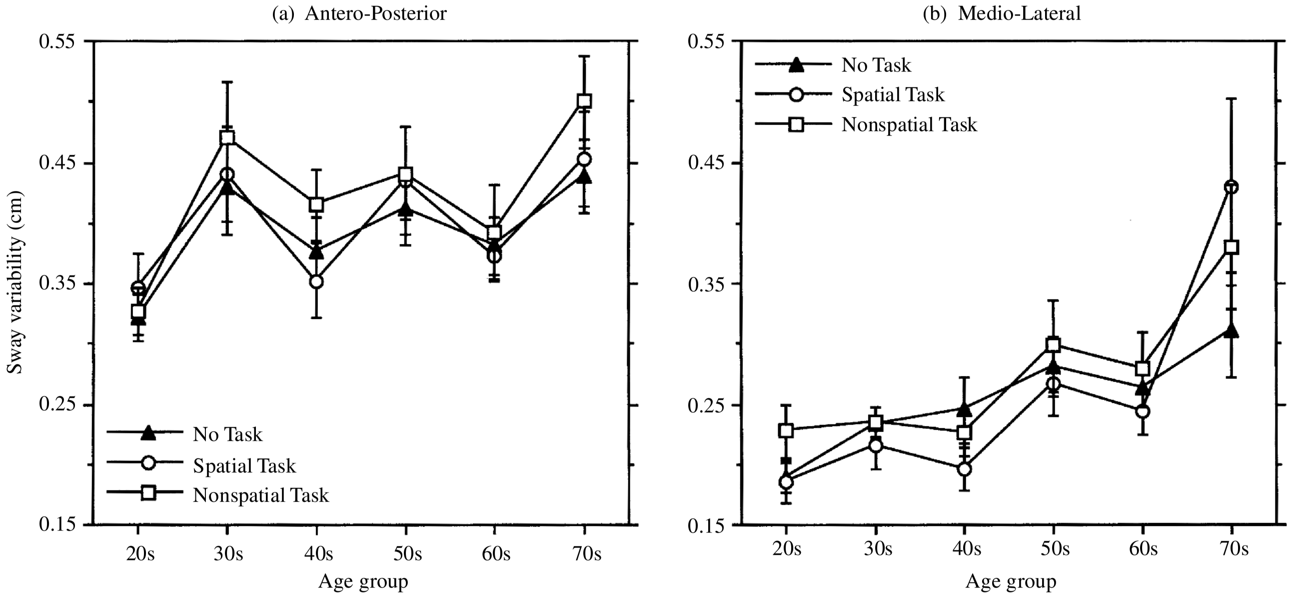

Figure 5. Mean sway variability (± 1 SE) for (a) antero-posterior, and (b) medio-lateral directions, as a function of age group and cognitive task.

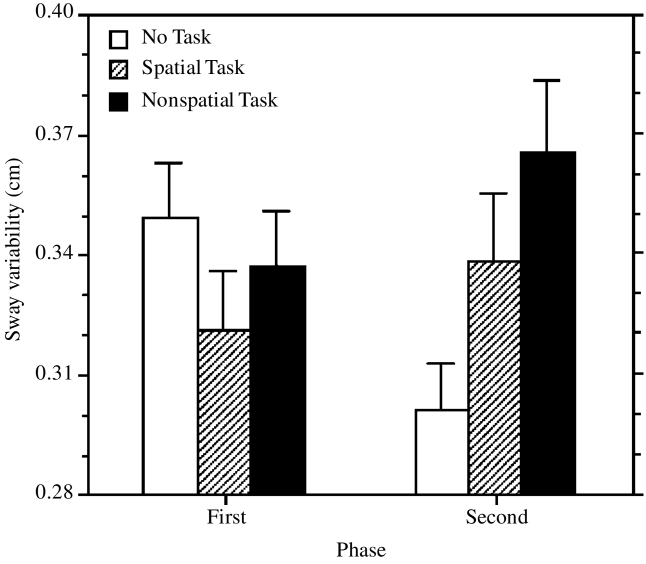

Figure 6. Mean sway variability (+ 1 SE) as a function of cognitive task and phase. For the spatial and nonspatial tasks, the first phase (0–15 seconds) corresponds to encoding and the second phase (15–25 seconds) corresponds to maintenance.

Again, the question arises as to whether the results for sway variability in Fig. 6 would be the same when considering spatial and nonspatial task conditions that produced approximately equivalent levels of cognitive performance (i.e. levels 1–3 for the spatial task vs. level 3 for the nonspatial task). As before, the pattern of results was largely unaffected; in this case, the mean sway variability values for the nonspatial task at level 3 were slightly lower than in Fig. 6 at 0.331 cm for the first phase, and 0.360 cm for the second phase.

Discussion

To summarize the present findings, there was age-related decline in cognitive performance in both the spatial and nonspatial memory tasks, as expected (see Craik & Jennings, 1992, and Kausler, 1994, for reviews of evidence for memory impairment with ageing). The spatial memory task with list lengths of 5, 6, and 7 was slightly more difficult overall than the nonspatial memory task with list lengths of 4, 5, and 6, but we were successful in our attempt to produce generally accurate performance in all conditions. There was virtually no effect of postural position (seated vs standing) on memory performance.

Postural stability as measured by sway velocity also declined with age, as expected (see Hill & Vandervoort, 1996, for a summary of similar findings). Although there were complex effects of both cognitive task and phase on sway velocity (see below), these were similar across all age groups. Thus there was little evidence in the sway velocity data of the effect observed by Maylor and Wing (1996) with a different measure of postural stability, namely, greater disruption from the spatial task in old age.

With sway variability as the measure of postural stability, there was greater age decline in the medio-lateral direction than in the antero-posterior direction (see Teasdale, Stelmach, & Breunig, 1991, for a similar finding). The antero-posterior data were generally quite noisy and failed to show the predicted Maylor and Wing (1996) effect. For the medio-lateral direction, however, there was significantly greater disruption to postural stability from the spatial task in comparison with no task for the 70s age group than for younger age groups. The sway variability data in the medio-lateral direction for the nonspatial task showed a similar trend, particularly for the most difficult condition that produced a similar level of cognitive performance to the spatial task.

Finally, for both sway velocity and sway variability (in both the antero-posterior and medio-lateral directions), there were striking interactions between cognitive task and phase (Figs 4 and 6). Thus in comparison with no task, sway was reduced by encoding stimuli (more so for the spatial than for the nonspatial task), but increased by maintaining stimuli (more so for the nonspatial than for the spatial task).

The first point to note is that despite instructions to give equal emphasis to the cognitive and postural control tasks (‘remember as many of the instructions as you can and stand as still as possible’), cognitive activity affected postural stability whereas the reverse was not the case, i.e. postural position had no effect on cognitive performance. This would appear to contradict a ‘posture first’ principle (e.g. Shumway-Cook *et al.*, 1997) such that where there is competition between tasks, postural control has priority and is therefore maintained at the expense of other tasks. However, it is clear that postural position can be shown to affect cognitive performance if more sensitive cognitive tasks and indices are employed (e.g. probe RT in LaJoie *et al.*, 1996b; random digit generation in Maylor & Wing, 1996), or if the postural control task is difficult (e.g. Tandem Romberg position in Kerr *et al.*, 1985).

The present study replicated Maylor and Wing’s (1996) finding of greater age differences in sway variability when performing the spatial task than when performing no task, although the effect was apparent only in the medio-lateral direction in the present study. Nevertheless, the presence here of an age interaction with cognitive task in at least one direction is important because it rules out an explanation in terms of differential effects of overt articulation on postural stability across adulthood. (Note that Maylor and Wing recorded postural stability throughout the spatial task, including during verbal recall.) In addition, the present study extends the Maylor and Wing result by demonstrating that the increase in age differences in postural stability with a spatial memory task (a) occurs between middle-age and old age (60s vs. 70s) but not between youth and middle-age (20s–60s), and (b) occurs for sway variability but not for sway velocity. This latter result is interpreted as indicating that spatial processing in older adults interferes specifically with the detection of, and/or speed of response to, large excursions of the centre of pressure from equilibrium.

An important feature of the present study was the direct comparison between the effects on postural stability of spatial and nonspatial cognitive tasks matched in most respects except for their spatial/nonspatial content. For sway variability in the medio-lateral direction, the difference between no task and the spatial task was significantly greater for the 70s age group (a 38% increase) than for the 20s–60s age groups (a 9% decrease), whereas the difference between no task and the nonspatial task was not significantly affected by age. These results would appear to support Maylor and Wing's (1996) conclusion that age differences in postural stability are increased by cognitive tasks specifically requiring visuo-spatial processing. However, the present spatial and nonspatial memory tasks were not perfectly matched in terms of cognitive performance and in fact the spatial memory task was more difficult than the nonspatial memory task, particularly for older participants. Importantly, for the nonspatial condition that produced a similar level of cognitive performance to the spatial task, the pattern of results with respect to age was qualitatively similar to that for the spatial task, with the difference in medio-lateral sway variability between no task and the nonspatial task being at least numerically much greater for the 70s age group (a 37% increase) than for the 20s–60s age groups (a 5% increase). In view of the relatively low power to detect age interactions in the present study, it would be premature to conclude that age differences in postural stability are increased only by cognitive tasks requiring visuo-spatial processing. Instead, it seems more likely that they can be increased by other cognitive tasks if they make sufficiently high demands on general processing resources. This would be consistent with suggestions that the attentional requirements of both cognitive and motor tasks are increased by normal ageing, so that demanding secondary tasks have greater adverse effects on motor performance in older than in younger adults (e.g. LaJoie, Teasdale, Bard, & Fleury, 1996a; Lindenberger *et al.*, in press).

It is important to emphasize that the present finding of greater disruption of postural stability from cognitive activity in old age (significant at least with a spatial task) was observed with healthy active older volunteers (as was also the case in Maylor & Wing, 1996). Thus the result is probably an underestimate of the true effect in the general population. A recent study by Shumway-Cook *et al.* (1997) examined the effects of cognitive activity on the postural stability of older adults with and without a history of falls in the previous six months. The standing balance of the fallers was more adversely affected by additional cognitive tasks than that of the nonfallers. An explanation for the difference is difficult because fallers and nonfallers differed in a number of ways (e.g. number of medications, proportion of female participants) but the study does raise the possibility that the effects of cognitive activity on postural stability may be more detrimental to less physically and mentally able older adults such as those who are frail or suffering from dementia. Clearly these are important issues for future research, particularly in view of the high rates of both falls (Blake *et al.*, 1988; Lord, 1996) and dementia (Jorm, 1990) in the elderly population.

In the present study, postural stability was measured separately for encoding and maintaining stimuli in the cognitive tasks. Novel and intriguing interactions emerged which were highly robust, consistent across all measures of postural stability and age groups, and largely unaffected by comparing spatial and nonspatial conditions matched in terms of cognitive performance. First, for encoding, sway was significantly reduced by the spatial task but only slightly reduced by the nonspatial task, in comparison with no task. This result could be interpreted as suggesting that encoding is not attentionally demanding, but this would be contrary to several dual task studies which have demonstrated that encoding interferes with secondary tasks such as manual RT (e.g. Anderson *et al*., 1998). However, the present result is not entirely unprecedented in the literature (cf. Fearing, 1925). Kerr *et al*. (1985) measured postural stability only while encoding stimuli and observed very similar trends, i.e. the reduction in sway from no task to the spatial task was on average 1.8 times greater than the reduction in sway from no task to the nonspatial task. Unfortunately, the spatial and nonspatial tasks in both Kerr *et al*.'s study and in the present study differed not only in terms of the spatial vs. nonspatial nature of the stimuli but also in terms of their rates of presentation. (In the present study there were no gaps between spatial stimuli but 1-second gaps between nonspatial stimuli.) Further work is necessary to determine which of these two factors (i.e. nature of stimuli or presentation rate) is responsible for the larger reduction in sway when encoding spatial than nonspatial stimuli. For now, the conclusion is that postural stability is not always unaffected or impaired by cognitive activity but can under some conditions be improved. One possibility is that a better focus for attention is provided by both auditory and visual information from a single location in space than by visual information alone. Another possibility is that participants may reduce their respiration rate or volume while encoding auditory stimuli, perhaps in order to enhance perception, thereby reducing sway. These and other possibilities require further investigation.

More importantly, for the second phase of maintaining stimuli, sway was significantly increased by both the spatial and nonspatial tasks in comparison with no task, with a larger increase for the nonspatial task. In this case, the difference between the spatial and nonspatial tasks cannot be attributed to any procedural differences. This result argues against Kerr *et al*.'s (1985) conclusion that there is interference between postural control and cognitive tasks only if visuo-spatial processing is required by the cognitive task. Clearly, nonspatial processing can interfere with postural stability, although it is not obvious why it should interfere more than spatial processing.

The present general pattern of reduced sway during encoding and increased sway during maintenance is reminiscent of the effects of cognitive activity on heart rate. Lacey and Lacey (1970, 1974) proposed that cardiac deceleration occurs when a situation requires the mental intake of environmental stimuli whereas cardiac acceleration occurs when mental elaboration or active processing of information is required (see De Pascalis, Barry, & Sparita, 1995; Jennings, 1986, 1992, for recent supportive evidence). It is unlikely that similar explanations apply to heart rate and postural control; nevertheless, the studies do illustrate that in order to understand interactions between cognitive activity and postural stability, further detailed studies are required which vary not only the type of cognitive task (e.g. spatial vs. nonspatial) but also the cognitive processing required (e.g. encoding vs. maintenance).

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