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RESEARCH ARTICLE

Task prioritization in aging: effects of sensory information on concurrent posture and memory performance

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Abstract In older adults, cognitive resources play a key role in maintaining postural stability. In the present study, we evaluated whether increasing postural instability using sway referencing induces changes in resource allocation in dual-task performance leading older adults to prioritize the more age-salient posture task over a cognitive task. Young and older adults participated in the study which comprised two sessions. In the first session, three posture tasks (stable, sway reference visual, sway reference somatosensory) and a working memory task (n-back) were examined. In the second session, single- and dual-task performance of posture and memory were assessed. Postural stability improved with session. Participants were more unstable in the sway reference conditions, and pronounced age differences were observed in the somatosensory sway reference condition. In dual-task performance on the stable surface, older adults showed an almost 40% increase in instability compared to single-task. However, in the sway reference somatosensory condition, stability was the same in single- and dual-task performance, whereas pronounced (15%) costs emerged for cognition. These results show that during dual-tasking while standing on a stable surface, older adults have the flexibility to allow an increase in instability to accommodate cognitive task performance. However, when instability increases by means of compromising somatosensory information, levels of postural control are kept similar in single- and dual-task, by utilizing resources otherwise allocated to the cognitive task. This evidence emphasizes the flexible nature of resource allocation, developed over the life-span to compensate for age-related decline in sensorimotor and cognitive processing.

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Introduction

Control of upright stance is achieved using sensory information from vestibular, visual and somatosensory channels, and this information is used to generate motor commands to the muscles for effective correction of deviations from stability. Evidence suggests that sensory perturbation of visual (Lestienne et al. 1977; Berthoz et al. 1979; Bronstein 1986), somatosensory (Johansson and Magnusson 1991; Jeka et al. 1997) and vestibular systems (Hlavacka and Njiokiktjien 1985; Johansson et al. 1995; Day et al. 1997) disrupts postural stability, however, the degree to which these systems contribute to postural control is also subject to age-related decline. Somatosensory function is considered to be the most important sensory source for postural control, contributing at least 60–75% of the information in standing on a stable surface (Horak et al. 1994; Peterka and Benolken 1995; Simoneau et al. 1995). This function is affected by aging, with older adults showing greater instability when somatosensory information is compromised using tendon vibration (Teasdale and Simoneau 2001), platform perturbations (Manchester et al. 1989) or sway referencing (Cohen et al. 1996; Speers et al. 2002; Forth et al. 2007).

Sway referencing is a way to compromise somatosensory or visual information, by means of rotating the support or the visual surround in the sagittal plane about the ankle joint axis in response to body sway. The amount of responsiveness of the support/surround is determined by a gain factor, with a gain of 1 resulting in movement of the support/surround at an exact proportion of the center of pressure (COP) movement, aiming to minimize sensory information in the affected modality. The effectiveness of this method was demonstrated in a study showing that sway in healthy adults under conditions with gain of 1 was found to be similar to sway in patients with diabetic (peripheral) neuropathy who stood on a stable surface (Horak et al. 2002) as well as in studies showing clear differences between healthy young and older adults (Cohen et al. 1996; Speers et al. 2002; Forth et al. 2007). In contrast, visual sway referencing did not reveal reliable age differences in the same studies. Previous research limited compromise of sensory information to a gain of 1 which may have been insufficient to elicit age differences, thus, based on the fact that an increase in gain causes instability in both sensory modalities (Clark and Riley 2006) in the present study we use a gain factor of 1.5.

Dual-task research has suggested that older adults recruit cognitive resources to compensate for age related decline in sensory and motor function (for reviews see Balasubramaniam and Wing 2002; Woollacott and Shumway-Cook 2002; Fraizer and Mitra 2007), especially in unstable and potentially dangerous situations. To that end, previous research suggests that the pattern of resource allocation in older adults is characterized by giving greater priority to the task with the greater importance, in this case postural control, because of the high prevalence of instabilities and falls in this age group (Fuller 2000). For instance, in dual-task performance involving memory retrieval while walking, when task difficulty increased with the addition of obstacles in their walking path, older adults' memory performance declined to maintain performance in walking, in other words, they prioritized walking over memory (Li et al. 2001). In a similar vein, in dual-task performance of posture and memory, increase in postural instability caused by platform movement triggered a decrease in memory performance in both older adults and Alzheimer's patients (Rapp et al. 2006). Presumably, resource limitations trigger a resource prioritization process in older adults, to protect them from potential falls. This prioritization is reflected in a decrease in cognitive task performance in dual- compared to single-task.

In the present study we asked, can we induce a change in resource allocation by increasing posture task difficulty using compromise in sensory information? To address this question, we used a dual-task paradigm comprising a posture task (stable platform, sway reference visual, sway reference somatosensory) and a working memory task (n-back: Dobbs and Rule 1989) for which the level of challenge was individually calibrated. The study included two sessions, the first included individual calibration of working memory performance and familiarization with the posture tasks, and the second included the contrast between single and dual-task performance. We predicted that older adults would show higher dual-task costs in postural stability than young adults, when performing a cognitive task while standing on a stable surface. In contrast, under conditions of compromised sensory information inducing more sway, we predicted that older participants would protect their posture at the cost of cognitive performance.

Method

Participants

Eighteen young (10 females, 8 males) and 18 older adults (10 females, 8 males) participated in the study, and were initially assessed using a series of screening tests. Screening tests included two marker tests from the WAIS (Wechsler 1981), digit symbol substitution (DSS) and digit span (DS). Young adults showed higher performance than older in the above tasks, as is common for these two age groups (e.g. Verhaeghen and Salthouse 1997). Furthermore, the mini mental state examination (MMSE, Psychological Assessment Resources, Inc.), and activities of daily living (ADL, Cumming et al. 2000) were also assessed. Detailed sample characteristics and test scores are given in Table 1. Participants reported no neurological or orthopaedic disorders, and they were not receiving medication known to affect postural control (Tillement et al. 2001; Ensrud et al. 2002). All participants gave informed consent prior to testing and were paid 20 € for their participation. The study was approved by the department's ethics committee.

Apparatus

In single-task cognitive performance participants sat at a table and visual stimuli were presented on a Pentium 4 PC

Table 1 Sample characteristics, group means and SDs for the screening tests

	Young	SD	Older	SD
Age	21.72	2.11	70.94	3.42
DSS score	87.06**	12.41	67.83	11.80
DSS time/item (s)	1.41**	0.22	1.82	0.32
DS Forward (items)	6.78*	1.86	5.44	1.92
DS Backward (items)	6.83*	1.98	5.67	1.41
MMSE	N/A	N/A	28.72	1.23
ADL	N/A	N/A	20	0

N/A Not applicable, * $P < 0.05$, ** $P < 0.01$

monitor. The programme for stimulus presentation was custom-written in Matlab (Mathworks, Natick, Mass., USA) using the Psychophysics Toolbox extensions (Brainard 1997; Pelli 1997). Postural control was assessed using the Balance Master Clinical Research System (NeuroCom International, Inc., Clackamas, OR, USA), which consists of mechanically locked dual force plates (AMTI), and a three-sided surround. Participants wore a safety harness and were asked to stand on the platform as still as possible. Visual stimuli were presented on a computer screen built into the system's visual surround. Vertical forces applied on the force plates were recorded at a sampling rate of 100 Hz, over the course of a 35 s trial. Cognitive task presentation started 5 s after posture recordings to allow participants to stabilize, thus, the first 5 s of the posture trial were excluded from analysis. Recorded force information was used to derive the medio-lateral (COP-X) and anterior–posterior (COP-Y) position–time functions of the COP for each trial. During sway-referenced conditions, the surface or the visual surround was servo-controlled to rotate in the sagittal plane about the ankle joint axis (e.g., toes-down or toes-up surface orientation) in response to estimated forward and backward center of mass (COM) sway angles. COM angles were estimated from the filtered COP-Y trajectory with a cut-off frequency of 0.5 Hz (Winter et al. 1996). In a gain setting of 1, the surround/support response rotates at an exact proportion of the participant's sway. Sway gain lower than 1 results in slower and smaller support/surround displacements and as a result signals less sway in the affected modality, whereas gain greater than 1 results in faster and greater displacements and a sensation of sensory information for sway in the opposite direction, causing greater instability (for details see Clark and Riley 2006). In the present study a gain factor of 1.5 was used in both sway referenced conditions.

Tasks and procedure

Data were collected in two sessions performed on different days, no more than a week apart. The cognitive task comprised a series of digits (one through nine) successively presented (stimulus duration 300 ms) on a computer screen, during the 30 s trial. Starting from the third digit, participants were asked to respond by articulating the digit presented two cycles before (2-back task). Cognitive performance for a given trial was calculated as the number of correctly articulated digits expressed as a percentage of the total number of digits.

In Session 1, an adaptive testing procedure was used, where the stimulus onset asynchrony (SOA), i.e. the time interval between stimulus onsets, was determined according to the participant's performance, to ensure that the task was equally challenging to all participants. SOA was gradually decreased from 2,500 (12 items) to 1,000 ms (30 items) at 6 levels of 3 trials each (2,500; 2,100; 1,800; 1,500; 1,200 and 1,000 ms). If performance exceeded 80% when the fastest SOA (1,000 ms) was reached, participants were asked to respond with the digit presented 3 cycles before (3-back task). Testing stopped at the SOA in which participants reached an average of 80% correct performance. The postural control tasks required participants to keep an upright stance on the force platform always with eyes open while articulating the digits appearing on the screen (0-back), in three different conditions: stable (no sway referencing), sway reference visual, and sway reference somatosensory. Blocks of cognitive and posture trials were presented in alternation, starting with a block of cognitive trials. In Session 1, participants always performed the stable platform condition first to ensure that they started with the least challenging condition, thereby being gradually familiarized with the challenging and highly unstable tasks, which is helpful for older adults. Then they performed the two sway-reference conditions counterbalanced.

In Session 2, single- and dual-task performance was assessed. In cognitive single-task trials participants were asked to perform the n-back task while seated, at the individually adjusted 80% level determined in Session 1. In posture single-task trials, they were instructed to stand as still as possible while naming the digits appearing on the screen (0-back). This task was used instead of standing without an additional task, to control for articulatory movements that increase postural instability (Yardley et al. 1999), thereby ensuring that the only additional component in dual-task performance was working memory. Dual-task assessment required participants to perform the n-back task at the 80% level while standing on the force platform. Each block comprised nine trials of a given posture condition, three single-task trials, followed by four dual-task trials and then by two single-task trials. This order made sure that possible improvement over the course of the nine trials did not affect the single- vs. dual-task comparison. The order of blocks was counterbalanced.

Data analysis

The anterio-posterior and medio-lateral components of the COP trajectory were first low-pass filtered (4th order Butterworth dual-pass filter, cutoff frequency: 10 Hz), and then an ellipse was fitted on the COP trajectory on the *x–y* plane using Principal Component Analysis. The length of the ellipse axes were equal to two standard deviations of the COP trajectory along each axis. Within the ellipse approximately 88% of the COP trajectory was fitted, thereby excluding outliers (for details on this method see Oliveira et al. 1996; Duarte and Zatsiorsky 2002). Increase in the size of the area covered by the ellipse reflects an increase in postural instability.

In Session 2, one of the initial three single-task posture trials in each condition, specifically the one with the largest ellipse area (i.e. with the greatest instability), was considered exploratory for each posture condition and was excluded from further analysis. Thus, 4 single and 4 dual task trials of each posture condition were analyzed. Square root transformation was applied to the ellipse area values prior to statistical analysis, to reduce outlier effects.

Proportional dual-task costs (DTCs) were also calculated. DTCs express the effects of the additional costs imposed in individual-task performance in a dual-task setting. DTCs were expressed as a percentage of single-task performance (proportional DTCs for posture: DTC_p and cognition: DTC_c) according to the formulae:

$$DTC_p = [(\text{dual-task} - \text{single-task}_p)/\text{single-task}_p] \times 100 \quad (1)$$

$$DTC_c = [(\text{single-task}_c - \text{dual-task})/\text{single-task}_c] \times 100. \quad (2)$$

It is important here to clarify the difference in the numerator of the two equations. Positive DTC_p are reflected in an increase in instability (ellipse area), thus we subtracted single from dual-task to obtain a positive value in the case of costs. Conversely, positive DTC_c are reflected in a decrease in accuracy (a lower value in percentage correct) in dual-task, therefore we subtracted dual from single-task to obtain a positive value, comparable to DTC_p.

Mixed design analyses of variance (ANOVAs) were used for comparisons of task conditions with age (young, older) being always the between-subjects factor. Within-subjects factors included posture condition (stable, sway reference visual, sway reference somatosensory), session (1, 2), task context (single-task, dual-task) and modality (cognition, posture). Reliable differences from a fixed value (zero in DTCs analysis, and 80% correct in accuracy in the n-back task) were assessed using one-sample *t* tests, which compare the mean of one sample to the fixed value.

Results

Improvement in stability and single-task posture effects

Figure 1 depicts postural stability effects, in Sessions 1 (Fig. 1a) and 2 (Fig. 1b). Ellipse areas in the different conditions were contrasted using a mixed-design ANOVA with age as between- and posture condition and session as within-subjects factors. Stability improved in the second session for both groups [$F(1,34) = 11.09$, $P < 0.01$], and this improvement was pronounced in the somatosensory sway referenced condition as shown by a posture condition by session interaction [$F(2,68) = 7.40$, $P < 0.01$]. The observed improvement in postural stability emphasizes the need for a sufficient number of single-task practice and familiarization trials before dual-task assessment, especially when the task is highly challenging and unstable. The above analysis also revealed that sway referencing caused an increase in postural instability especially when somatosensory information was compromised [$F(1,34) = 60.47$, $P < 0.01$]. Older adults were more unstable (greater ellipse areas) than young adults [$F(1,34) = 6.02$, $P < 0.05$] but only in the somatosensory sway referenced condition which showed the greatest instability as shown by a posture condition by age interaction [$F(2,68) = 33$, $P < 0.05$].

Dual-task effects

Results for working memory performance in single- (while seated) and dual-task (while performing one of the three posture conditions) are depicted in Fig. 2. The cognitive task was performed as required, keeping both young and older adults' baseline (single-task) performance at the same

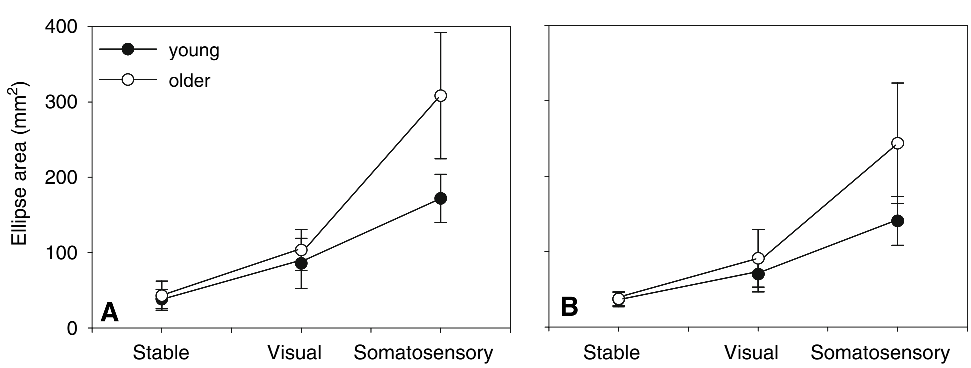

Fig. 1 Posture performance measured as the area of the fitted ellipse in **a**: Session 1, and **b**: Session 2, in the three sway referenced conditions for young and older adults. In both sessions participants were standing on the platform while articulating the numbers appearing on the screen (Single-task posture). *Error bars* represent ±2 standard errors of the mean (SE)

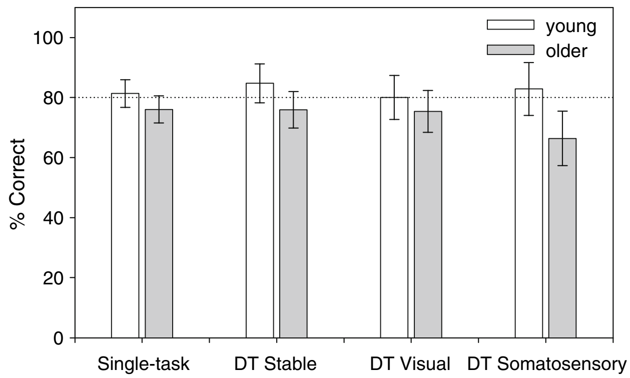

Fig. 2 Performance in working memory measured as the number of successive correct items in the n-back task, as a percentage of the number of items in a given trial. Single-task performance represents the average of the trials performed while seated throughout Session 2, and dual-task (DT) performance is plotted for each of the posture conditions. *Error bars* represent ±2 SE of the mean (SE)

level, as shown by the lack of group differences [$t(34) = 2.032$, $P = 0.11$]. Performance of both age groups in working memory was not different from the targeted 80% accuracy level, as confirmed by one-sample t tests. Accuracy in working memory was analyzed using three separate mixed-design ANOVAs with age as between, and task context (single-task contrasted with each of the three dual-task conditions seperately) as within-subjects factors. Results showed that in dual-task performance in the sway reference somatosensory condition, older adults exhibited a decrease in accuracy relative to single task, as indicated by an age by task context interaction [$F(1,34) = 4.63$, $P < 0.05$]. This interaction was not present in the other two posture conditions. Furthermore, older adults exhibited lower accuracy than young adults in two of the three comparisons, indicated by main effects of age [single vs. stable $F(1,34) = 4.44$; single vs. somatosensory $F(1,34) = 6.436$, $P < 0.05$].

In posture performance, there were limitations in contrasting absolute values of ellipse area in single- and dual-task performance, primarily because values in stable and sway reference conditions were in different orders of magnitiude (see Fig. 1). Thus, proportional DTCs which take into account absolute differences, thereby controlling for differences in order of magnitude, were considered more approporiate to assess dual-task effects.

Dual-task costs

DTCs in posture (Fig. 3a) were reliably different from zero only for older adults in the stable platform condition [$t(17) = 3.399$, $P < 0.01$], suggesting that older adults allow almost 40% increase in instability to accommodate the additional challenge introduced by the concurrently performed cognitive task. DTCs in cognition (Fig. 3b), were reliably different from zero only for older adults in the sway reference somatosensory condition [$t(17) = 2.84$, $P < 0.05$] suggesting that when instability increases, older adults direct part of their cognitive resources to posture, and that has a cost for performance in memory. Costs in the visual sway reference condition were not reliably different from zero for both age groups, and were excluded from further analysis.

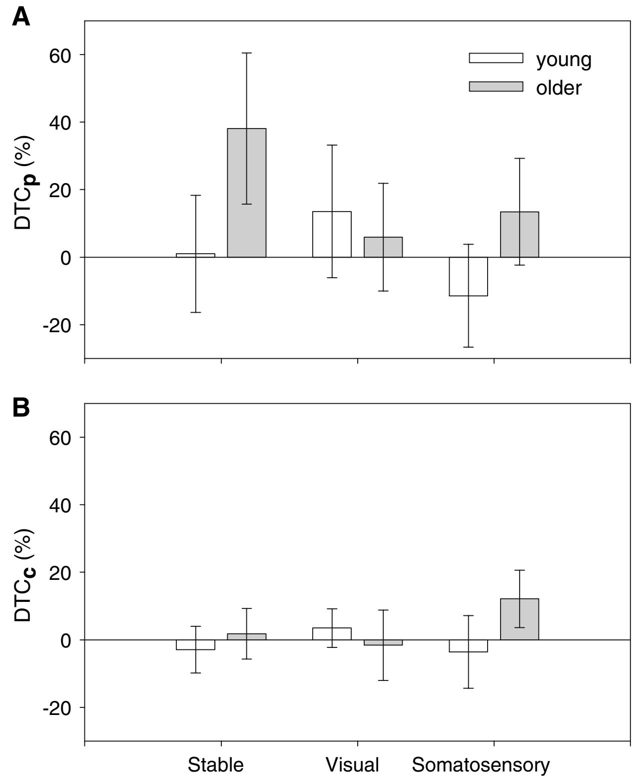

Fig. 3 Proportional DTCs in **a**: Posture and **b**: Working memory, for young and older adults in the three posture conditions. *Error bars* represent ±2 SE of the mean

To assess differences in proportional DTCs a mixed-design ANOVA with age (young, old) as between- and modality (posture, cognition) and posture condition (stable, sway reference somatosensory) as within-factors was performed. Overall, older adults exhibited greater costs than young adults (Fig. 3a, b) as shown by a main effect of age [$F(1,34) = 15.84$, $P < 0.01$]. In older adults, DTCs in posture were greater than in cognition, as shown by a modality by age interaction [$F(1,34) = 4.27$, $P < 0.05$]. More importantly, a modality by posture task interaction [$F(1,34) = 7.18$, $P < 0.05$] revealed that in posture, DTCs dropped when instability increased in the somatosensory sway reference condition, whereas in cognition this increase in instability caused a rise in costs. This interaction supports our prediction for a trade-off relation in costs when task difficulty in posture increases. However, our prediction suggests that this trade-off relation would only be observed in older adults, thus, we conducted the above analysis for young and older adults separately. Indeed, the modality by posture task interaction [$F(1,17) = 6.54$, $P < 0.05$] was only observed in older adults, supporting our prediction. Again, costs in posture were greater than in cognition as shown by a main effect of modality [$F(1,17) = 5.39$, $P < 0.05$] only in older adults.

Discussion

Our goal was to induce adaptive resource allocation in older participants by compromising visual or somatosensory information. Both manipulations were successful, but only somatosensory led to pronounced age-effects in posture. These sizeable age differences shown only when somatosensory information was compromised, suggest that somatosensory processing for posture is sensitive to age related decline, in agreement with past evidence (Manchester et al. 1989; Cohen et al. 1996; Teasdale and Simoneau 2001; Speers et al. 2002; Forth et al. 2007). Having established clear age differences in postural stability, we then focused on the way cognitive resources are used for posture control, by adding a concurrently performed cognitive task. Dual-task performance presented no additional instability for young adults, however, in the stable platform condition older adults allowed an almost 40% increase in instability to accommodate accurate cognitive task performance. Conversely, when posture was challenged (sway referenced somatosensory) older adults did not allow additional instability, instead they maintained stability to almost the same degree in single- and dual-task performance. This maintenance or protection of postural stability in the most challenging condition had a cost for cognitive task performance which showed a 15% decline.

Our results suggest that when posture is relatively stable, older adults have the flexibility to allow additional instability, perhaps with a risk for posture, to release the resources necessary to accommodate the demands of dual-task performance. However, when instability increases, the sensorimotor task requires more resources (Li et al. 2001; Rapp et al. 2006), and to maintain stability these resources are not released, thereby failing to achieve accurate cognitive task performance. That way, older adults protect their posture and prioritize it over cognitive performance, possibly to prevent additional instability and a potential fall. Our findings emphasize the highly flexible nature of resource allocation in older adults and are in agreement with a previous study by Rapp et al. (2006) suggesting that older adults develop this flexibility through long-term adaptation, to compensate for age-related decline in sensorimotor processing.

A similar view, emphasizing the adaptive nature of postural control in a dual-task setting, but in young adults, has been proposed by Mitra and colleagues (Mitra 2003, 2004; Mitra and Fraizer 2004). Evidence in this view suggests that young adults show adaptive resource-sharing depending on the different dual-task settings, reflected in facilitation effects (reduced sway), i.e. negative DTC in posture. Depending on the nature of instructions or the cognitive task challenge these facilitation effects can be transformed (Mitra and Fraizer 2004), to response-competition i.e. positive DTC in posture, similar to the ones observed in the present study in older adults. Older adults mostly show positive costs, and adaptive resource allocation is reflected in trade-off relations following increased task difficulty, as demonstrated in the present and in previous studies (Li et al. 2001; Rapp et al. 2006). It is possible to show reduced sway in older but not young adults, but this has been so far shown only when postural control was threatened (Brown et al. 2002), not using a concurrent cognitive task. A direct assessment of age differences using tasks similar to the ones by Mitra and colleagues adapted for older adults would add to our understanding of the changes in resource-sharing mechanisms over the life-span.

Although posture and dual-task effects were clear when somatosensory information was compromised, visual sway referencing did not reveal effects of age and dual-tasking although we used a greater gain level (1.5) than previous studies (Cohen et al. 1996; Speers et al. 2002; Forth et al. 2007). Similarly, past evidence suggests that effects of vision on posture are observed only when somatosensory as well as visual information is compromised, for instance in older adults with age-related maculopathy standing on a compliant (foam) surface (Elliott et al. 1995). Together, these results show that compromise of visual information only is not adequate to produce age differences in postural stability, possibly because somatosensory and vestibular information compensate for the caused instability.

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References

Balasubramaniam R, Wing AM (2002) The dynamics of standing balance. Trends Cogn Sci 6:531–536

Berthoz A, Lacour M, Soechting JF, Vidal PP (1979) The role of vision in the control of posture during linear motion. Prog Brain Res 50:197–209

Brainard DH (1997) The psychophysics toolbox. Spat Vis 10:433–436

Bronstein AM (1986) Suppression of visually evoked postural responses. Exp Brain Res 63:655–658

Brown LA, Sleik RJ, Polych MA, Gage WH (2002) Is the prioritization of postural control altered in conditions of postural threat in younger and older adults? J Gerontol A Biol Sci Med Sci 57A:M785–M792

Clark S, Riley MA (2006) Multisensory information for postural control: sway-referencing gain shapes center of pressure variability and temporal dynamics. Exp Brain Res 176(2):299–310

Cohen H, Heaton LG, Congdon SL, Jenkins HA (1996) Changes in sensory organization test scores with age. Age Ageing 25:39–44

Cumming RG, Salkeld G, Thomas M, Szonyi G (2000) Prospective study of the impact of fear of falling on activities of daily living, SF-36 scores, and nursing home admission. J Gerontol A Biol Sci Med Sci 55:M299–305

Day BL, Severac Cauquil A, Bartolomei L, Pastor MA, Lyon IN (1997) Human body-segment tilts induced by galvanic stimulation: a vestibularly driven balance protection mechanism. J Physiol 500(Pt 3):661–672

Dobbs AR, Rule BG (1989) Adult age differences in working memory. Psychol Aging 4:500–503

Duarte M, Zatsiorsky VM (2002) Effects of body lean and visual information on the equilibrium maintenance during stance. Exp Brain Res 146:60–69

Elliott DB, Patla AE, Flanagan JG, Spaulding S, Rietdyk S, Strong G, Brown S (1995) The Waterloo vision and mobility study: postural control strategies in subjects with ARM. Ophthalmic Physiol Opt 15:553–559

Ensrud KE, Blackwell TL, Mangione CM, Bowman PJ, Whooley MA, Bauer DC, Schwartz AV, Hanlon JT, Nevitt MC (2002) Central nervous system-active medications and risk for falls in older women. J Am Geriatr Soc 50:1629–1637

Forth KE, Metter EJ, Paloski WH (2007) Age associated differences in postural equilibrium control: a comparison between EQscore and minimum time to contact [TTC (min)]. Gait Posture 25: 56–62

Fraizer EV, Mitra S (2007) Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. Gait Posture 27(2):271–279

Fuller GF (2000) Falls in the elderly. Am Fam Physician 61:2159–2168

Hlavacka F, Njiokiktjien C (1985) Postural responses evoked by sinusoidal galvanic stimulation of the labyrinth. Influence of head position. Acta Otolaryngol 99:107–112

Horak FB, Dickstein R, Peterka RJ (2002) Diabetic neuropathy and surface sway-referencing disrupt somatosensory information for postural stability in stance. Somatosens Mot Res 19:316–326

Horak FB, Shupert CL, Dietz V, Horstmann G (1994) Vestibular and somatosensory contributions to responses to head and body displacements in stance. Exp Brain Res 100:93–106

Jeka JJ, Schoner G, Dijkstra T, Ribeiro P, Lackner JR (1997) Coupling of fingertip somatosensory information to head and body sway. Exp Brain Res 113:475–483

Johansson R, Magnusson M (1991) Human postural dynamics. Crit Rev Biomed Eng 18:413–437

Johansson R, Magnusson M, Fransson PA (1995) Galvanic vestibular stimulation for analysis of postural adaptation and stability. IEEE Trans Biomed Eng 42:282–292

Lestienne F, Soechting J, Berthoz A (1977) Postural readjustments induced by linear motion of visual scenes. Exp Brain Res 28:363–384

Li KZH, Lindenberger U, Freund AM, Baltes PB (2001) Walking while memorizing: A SOC study of age-related differences in compensatory behavior under dual-task conditions. Psychol Sci 12:230–237

Manchester D, Woollacott M, Zederbauer-Hylton N, Marin O (1989) Visual, vestibular and somatosensory contributions to balance control in the older adult. J Gerontol A Biol Sci Med Sci 44:M118–127

Mitra S (2003) Postural costs of suprapostural task load. Hum Mov Sci 22:253–270

Mitra S (2004) Adaptive utilization of optical variables during postural and suprapostural dual-task performance: comment on Stoffregen, Smart, Bardy, and Pagulayan (1999). J Exp Psychol Hum Percept Perform 30:28–38

Mitra S, Fraizer E (2004) Effects of explicit sway-minimization on postural-suprapostural dual-task performance. Hum Move Sci 23:1–20

Oliveira LF, Simpson DM, Nadal J (1996) Calculation of area of stabilometric signals using principal component analysis. Physiol Meas 17:305–312

Pelli DG (1997) The VideoToolbox software for visual psychophysics: transforming numbers into movies. Spat Vis 10:437–442

Peterka RJ, Benolken MS (1995) Role of somatosensory and vestibular cues in attenuating visually induced human postural sway. Exp Brain Res 105:101–110

Rapp M, Krampe RT, Baltes PB (2006) Adaptive task prioritization in aging: Selective resource allocation to postural control is preserved in Alzheimer disease. Am J Geriatr Psychiatry 14:52–61

Simoneau GG, Ulbrecht JS, Derr JA, Cavanagh PR (1995) Role of somatosensory input in the control of human posture. Gait Posture 3:115–122

Speers RA, Kuo AD, Horak FB (2002) Contributions of altered sensation and feedback responses to changes in coordination of postural control due to aging. Gait Posture 16:20–30

Teasdale N, Simoneau M (2001) Attentional demands for postural control: the effects of aging and sensory reintegration. Gait Posture 14:203–210

Tillement JP, Albengres E, Cottin D, Klouz A, Arkoub H, Le Louet H (2001) The risk of falling due to benzodiazepine administration, alone or in combination, in elderly subjects. Therapie 56:435–440

Verhaeghen P, Salthouse TA (1997) Meta-analyses of age-cognition relations in adulthood: Estimates of linear and nonlinear age effects and structural models. Psychol Bull 122:231–249

Wechsler D (1981) WAIS-R manual. Psychological Corp., New York

Winter DA, Prince F, Frank JS, Powell C, Zabjek KF (1996) Unified theory regarding A/P and M/L balance in quiet stance. J Neurophysiol 75:2334–2343

Woollacott M, Shumway-Cook A (2002) Attention and the control of posture and gait: A review of an emerging area of research. Gait Posture 16:1–14

Yardley L, Gardner M, Leadbetter A, Lavie N (1999) Effect of articulatory and mental tasks on postural control. Neuroreport 10:215–219