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Attentional costs of walking are not affected by variations in lateral balance demands in young and older adults

Masood Mazaheri [a,*], Melvyn Roerdink [a], Jacques Duysens [b], Peter J. Beek [a], C. (Lieke) E. Peper [a]

[a] *MOVE Research Institute Amsterdam, Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands*
[b] *Department of Kinesiology, KU-Leuven, Belgium*

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ABSTRACT

Increased attentional costs of walking in older adults have been attributed to age-related changes in visuomotor and/or balance control of walking. The present experiment was conducted to examine the hypothesis that attentional costs of walking vary with lateral balance demands during walking in young and older adults. Twenty young and twenty older adults walked on a treadmill at their preferred walking speed under five conditions: unconstrained normal walking, walking on projected visual lines corresponding to either the participant's preferred step width or 50% thereof (i.e. increased balance demand), and walking within low- and high-stiffness lateral stabilization frames (i.e. lower balance demands). Attentional costs were assessed using a probe reaction-time task during these five walking conditions, normalized to baseline performance as obtained during sitting. Both imposed step-width conditions were more attentionally demanding than the three other conditions, in the absence of any other significant differences between conditions. These effects were similar in the two groups. The results indicate that the attentional costs of walking were, in contrast to what has been postulated previously, not influenced by lateral balance demands. The observed difference in attentional costs between normal walking and both visual lines conditions suggests that visuomotor control processes, rather than balance control, strongly affect the attentional costs of walking. A tentative explanation of these results may be that visuomotor control processes are mainly governed by attention-demanding cortical processes, whereas balance is regulated predominantly subcortically.

1. Introduction

Limited ability to adjust walking to task and environmental demands increases fall risk in elderly persons [1]. An important aspect of walking adaptability is the ability to cope with variations of attentional demands associated with performing secondary tasks while walking [1,2]. An age-related increase in the attentional demands of walking may hamper an individual's ability to respond to environmental hazards with potentially serious consequences. Indeed, such age-related changes are associated with less safe gait, poor mobility, increased dependence in activities of daily living and particularly increased fall risk [3].

The interaction between walking and attention has most commonly been assessed using dual-task paradigms in which walking is performed simultaneously with a secondary cognitive task [4]. Competition for limited attentional resources between the primary and secondary task may result in interference or decrement in performance of either one or both tasks when compared with their baseline single-task performances. Lundin-Olsson et al. [3] showed that older adults who are not able to continue walking while talking are more prone to falling than those who can perform the two tasks simultaneously. More recent studies [5–7] support increased dual-task interference with aging, suggesting that walking is more attentionally demanding in older than in young adults.

Increased attentional costs of walking among older adults may be attributed to subtle brain impairments or disorders in the coordination of sensory and motor information required for performing complex abilities, such as balance regulation during walking. Previous research revealed that in older adults both

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* Corresponding author at: MOVE Research Institute Amsterdam, Department of Human Movement Sciences, Faculty of Behavioural and Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands. Tel.: +31 20 5982632.
E-mail address: m.mazaheri@vu.nl (M. Mazaheri).

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cognitive impairments [8] and elevated visuomotor demands [9–12] are associated with increased attentional costs of walking. Few studies [13,14], however, have specifically addressed how balance control affects the attentional costs of walking, especially in older adults. Pertinent evidence comes primarily from experiments with base-of-support manipulations, showing that attentional costs are higher during walking than during standing or sitting [9,10,13,14]. Although balance requirements may change over the gait cycle, inconsistent results have been reported regarding the attentional costs for specific phases in the gait cycle [13–15]. However, balance demands were never manipulated systematically during the gait cycle as a whole, which precludes drawing firm conclusions about the effect of balance control on the attentional costs of walking. In the present study, we focused on lateral stability manipulations because walking is less passively stable in mediolateral direction than in fore-aft direction [16]. Active sensorimotor control required for lateral balance during walking may be expected to elevate the attentional costs of walking.

In particular, we examined the effect of variations in lateral balance demands on attentional costs of walking in both young and older adults. Balance demands were manipulated by means of two levels of prescribed step width (SW; preferred vs. narrower than preferred, imposed by means of visual lines projected onto the walking surface) and a lateral stabilization device (involving two levels of mechanical stabilization [17]). With these manipulations, we created conditions with higher and lower balance demands, respectively. The attentional costs associated with these conditions were assessed with vibrotactile stimulus-response reaction times (RT) [9,10]. We expected that higher balance demands (as evoked by walking with a narrow base of support) would increase the attentional costs of walking, particularly in older adults. Likewise, we expected that lower balance demands (as evoked by lateral stabilization) would reduce the attentional costs of walking, again particularly in older adults.

2. Material and methods

2.1. Participants

Twenty young adults (female/male: 12/8) and 20 healthy older adults (female/male: 12/8) participated in the experiment (Table 1). Participants had no self-reported cardiovascular or cardiopulmonar problems, orthopedic conditions, uncorrected visual or auditory impairments, neurological disease, or other conditions limiting mobility; they did not use walking aids and the Mini Mental State Exam score for the older participants exceeded 23 (range 24–30). All participants provided written informed consent before participation. The departmental ethics committee approved the experiment.

Table 1
Participants' demographic and clinical characteristics per group.

	Young adults (f/m: 12/8)	Older adults (f/m: 12/8)	Group comparisons	
			Statistics	*p*-value
Age (year)	23.2 ± 3.3	72.9 ± 4.6	$t_{38} = 39.13$	<0.001
Height (cm)	174.5 ± 9.6	170.9 ± 10.2	$t_{38} = 1.15$	0.26
Weight (kg)	64.6 ± 10.8	66.6 ± 10.2	$t_{37} = 0.60$	0.56
CWS (km/h)	4.2 ± 0.6	3.7 ± 0.7	$t_{38} = 2.43$	0.02
FRD (cm)	35.2 ± 7.6	29.4 ± 6.1	$t_{38} = 2.64$	0.01
Baseline RT (ms)	233.5 ± 25.0	297.3 ± 31.8	$t_{38} = 7.05$	<0.001

Notes: values are mean ± SD. CWS, comfortable walking speed; FRD, functional reach distance; RT, reaction time; and f/m, female/male.

2.2. Experimental set-up

The experimental set-up was designed to induce higher and lower balance demands, using two separate manipulations: prescribed SW and lateral stabilization. A force-platform instrumented dual-belt treadmill (Motekforce Link, Amsterdam/Culemborg, The Netherlands) equipped with a projector allowing projection of visual lines onto the belt's surface was used to measure and impose SW in the prescribed conditions (Fig. 1A). In the lateral stabilization conditions, an external stabilizer [17] (Fig. 1B) was used to enhance lateral stability. Two spring-like rubber cords were attached to a frame fastened to the waist and anchored to ball-bearing trolleys that moved freely in for-aft direction within a horizontal rail parallel to the ground, positioned at either side of the participant. The height of the rail was adjusted to the participant's waist height. Cords with two different levels of stiffness (low stiffness: 760 Nm^{-1} and high stiffness: 1613 Nm^{-1}, see [17]) were used, with the high-stiffness level providing larger stability.

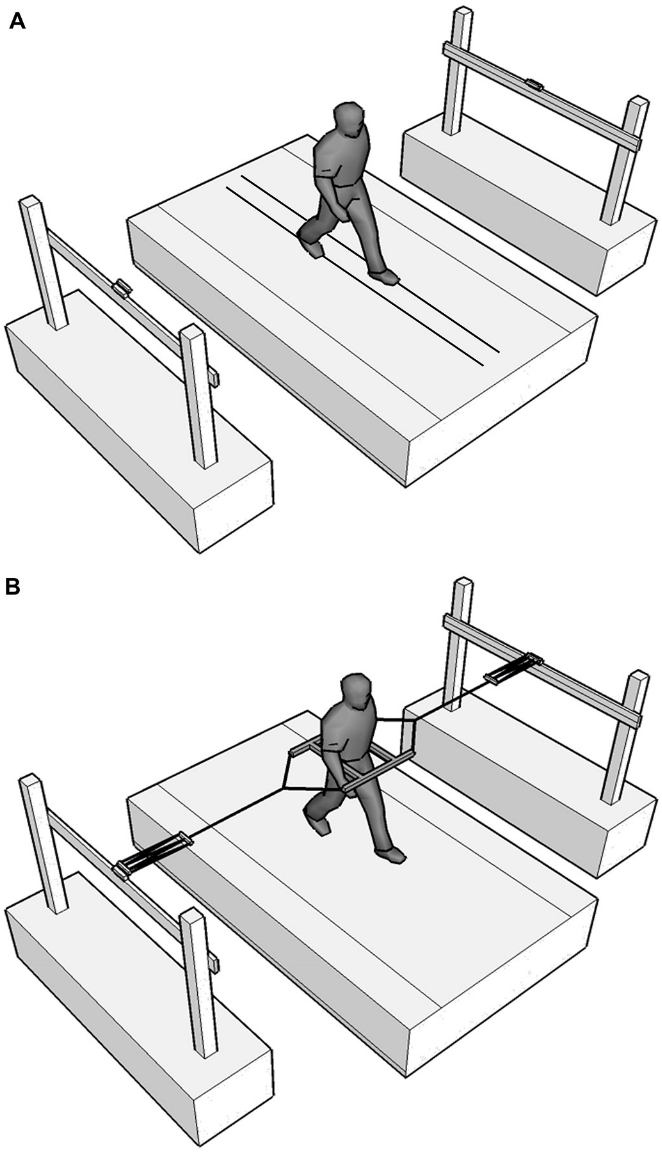

Fig. 1. Schematic of the experimental conditions to vary lateral balance demands. (A) Walking on visual lines projected onto the treadmill belt; (B) Walking with external lateral stabilizer with a spring-like cord attached to the light-weight frame fastened to the waist belt on one end and on the other end to the ball-bearing trolley.
Figure adapted with permission from J Biomech 2013;46:2109–14.

Stimulus-response RT was measured using a custom-made stimulus vibrator (pulse duration: 300 ms; attached to the non-dominant hand's wrist) and a response button (sampling rate: 1000 Hz; held in the dominant hand; [9,10]). A safety harness to protect participants from falling was used in all walking conditions that did not involve the external stabilization frame.

A horizontally oriented tape measure attached to the wall at the height of the participant's acromion process was used in the Functional Reach Test (FRT).

2.3. Procedure

2.3.1. Preparation

Participants first practiced treadmill walking for 10 min. Next, comfortable walking speed (CWS) was determined by first increasing treadmill speed (in 0.1 km/h steps) until the participant reported his/her CWS was reached. After a 1.5 km/h increment, walking speed was decreased (0.1 km/h steps) until CWS was indicated again [10]. The average of these two subjective estimates served as the participant's CWS and was used for all subsequent walking conditions. Next, each participant's preferred SW at his/her CWS was determined (1 min).

Participants' balance ability was quantified as the functional reach distance (FRD) using the FRT [18].

2.3.2. Experiment

Participants walked under two prescribed SW conditions and two lateral stabilization conditions. For the prescribed SW conditions, the distance between the two visual lines projected onto the treadmill belt's surface was set to 100% (preferred SW condition) or 50% (narrow SW condition) of each participant's preferred SW as determined in the pre-experimental trial. Participants were instructed to align the midline of their shoes with the visual lines. The lateral stabilization conditions involved walking with either low- or high-stiffness stabilizers. In these conditions, no visual lines were presented. Participants were familiarized with walking on the visual lines (1 min) and walking with the lateral stabilizer (5–10 min) prior to the corresponding experimental trials.

During each walking trial RT was assessed using 21 vibratory stimuli. To control gait cycle effects on attentional costs [13,14], RTs were presented at the moment of heel strike of either the left or the right foot (equally distributed, random order) [10]. The first stimulus served as warning cue and appeared at least 5 s after the trial had started. Inter-stimulus intervals varied randomly between 3 and 17 s. Participants had to press the button as soon as they felt the vibration, but were asked to prioritize the walking task [4].

The experiment consisted of two blocks, which were counterbalanced across participants: one with prescribed SWs (preferred and narrow), the other with lateral stabilization (low and high stiffness). In each block, conditions were presented in random order, with two consecutive trials per condition. In addition, each block comprised one control condition involving unconstrained walking, yielding five dual-task walking trials in total per block. Prior to the first and after the second block of trials a baseline RT trial was conducted, measuring RT while sitting on a chair. Two single-task unconstrained walking trials (i.e. without RT) were also conducted, one prior to the first sitting trial and one between the two blocks. All trials lasted 2.5 min. Sufficient rest periods were administered between trials and blocks to prevent fatigue.

2.4. Data analysis

All data were analyzed using custom-made Matlab (Mathworks, Natick, MA, USA) scripts. The RT obtained for the first stimulus in each trial (warning cue) was eliminated, as were RTs $<$120 ms and $>$1100 ms [10]. Accordingly, 9 stimulus-response pairs were discarded in the older group (i.e. $<$0.01%; lateral stabilization: 2; prescribed SW: 7). No response was detected for 28 stimuli (i.e. $<$0.01%; young: 7, older: 21; predominantly for prescribed SW: 14). RT was defined as the median of the remaining time intervals between stimulus and response onsets per trial, and subsequently averaged over the two trials per condition. To eliminate individual baseline differences, attentional costs were characterized as difference scores ($\Delta RT = RT_{walking\ condition} - RT_{sitting}$) and proportional difference scores ($\Delta RT_{prop} = [RT_{walking\ condition} - RT_{sitting}]/RT_{sitting}$).

For each prescribed SW trial, the actually performed SW was determined from the force-plate data by taking the median of the absolute differences between left and right mediolateral center-of-pressure positions at mid-stance (i.e. halfway between foot contact and foot off). SW was averaged over the two trials per condition and normalized to the imposed SW. SW could not be reliably determined for one older participant in the imposed SW conditions because gait events were not well demarcated. For the unconstrained walking tasks, step width, stride length, stride time and cadence were determined.

2.5. Statistical analysis

Age, height, weight, CWS, FRD and baseline RT were compared between the two groups using independent *t*-tests. To examine the adherence to the imposed SW conditions, normalized SW was subjected to a 2 (group: young vs. older adults) by 2 (task: preferred vs. narrow SW) mixed-model ANOVA. The effects of age and lateral balance demands on ΔRT and ΔRT_{prop} were examined using 2 (group) by 5 (task: narrow SW, preferred SW, unconstrained walking, low-stiffness stabilizer, high-stiffness stabilizer) mixed-model ANOVAs. To examine whether the RT task affected gait, gait parameters were compared between unconstrained walking with and without RT, using a 2 (group) by 2 (task: with vs. without RT) mixed-model ANOVA. Alpha level was set at 0.05. Paired *t*-tests (with Bonferroni correction) were used for post hoc pair-wise comparisons. Partial eta squared (η_p^2) and Hedges' g_{av} (g_{av}) were used to determine effect size [19].

3. Results

Table 1 presents the participants' demographic and test characteristics. CWS and FRD scores were significantly lower in older adults. Baseline RT was significantly higher in older adults.

The ANOVA on normalized SW yielded a significant main effect of task ($F_{1,37} = 244.94$, $p < 0.001$; $\eta_p^2 = 0.87$): normalized SW was larger for the preferred SW condition than for the narrow SW condition (88% ± 9% vs. 55% ± 12%). The absence of a significant group effect ($F_{1,37} = 0.22$, $p = 0.64$; $\eta_p^2 = 0.01$) or group by task interaction ($F_{1,37} = 0.72$, $p = 0.40$; $\eta_p^2 = 0.02$) indicated that both groups adhered to the task in a similar fashion.

A significant main effect of task on both ΔRT measures was observed (ΔRT: $F_{4,152} = 83.58$, $p < 0.001$; $\eta_p^2 = 0.69$; ΔRT_{prop}: $F_{4,152} = 89.69$, $p < 0.001$; $\eta_p^2 = 0.70$; Fig. 2). Post hoc analysis showed that ΔRT and ΔRT_{prop} were larger for the two prescribed SW conditions than the other three conditions (ΔRT: preferred SW: g_{av}'s > 1.35; narrow SW: g_{av}'s > 1.36; ΔRT_{prop}: preferred SW: g_{av}'s > 1.23; narrow SW: g_{av}'s > 1.19), whereas neither the two SW conditions (ΔRT: $g_{av} = 0.05$; ΔRT_{prop}: $g_{av} = 0$) nor the other three conditions (ΔRT: g_{av}'s < 0.12; ΔRT_{prop}: g_{av}'s < 0.08) differed significantly from each other. The main effect of group (ΔRT: $F_{1,38} = 0.97$, $p = 0.33$; $\eta_p^2 = 0.03$; ΔRT_{prop}: $F_{1,38} = 1.38$, $p = 0.25$; $\eta_p^2 = 0.04$) and the group by task interaction (ΔRT: $F_{4,152} = 0.80$,

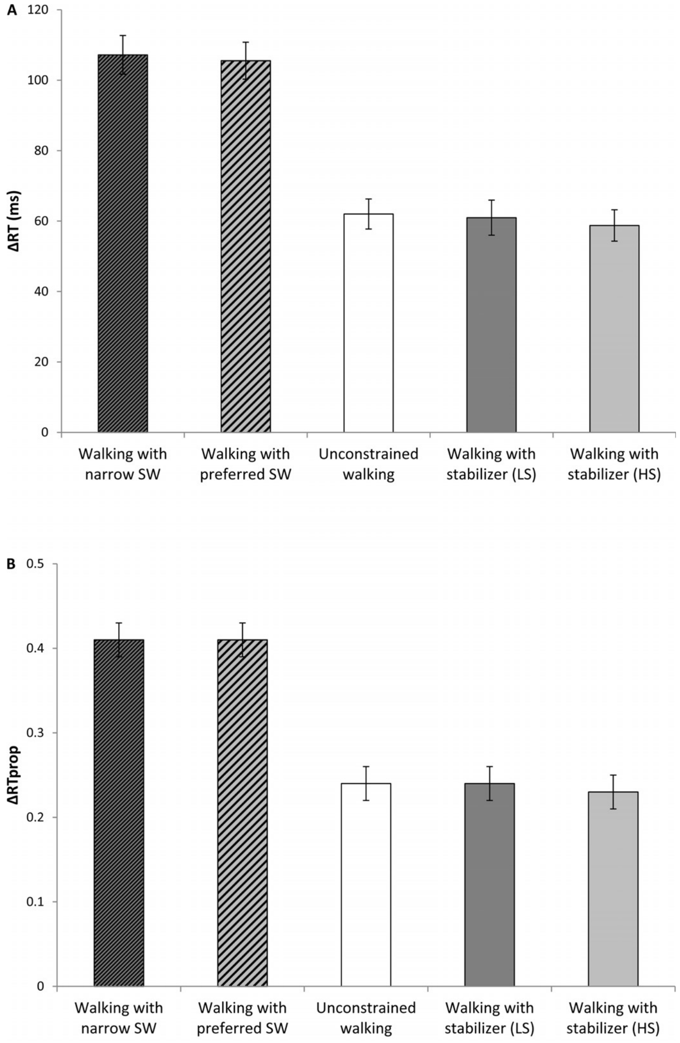

Fig. 2. Mean ΔRT (panel A) and ΔRT_{prop} (panel B) for walking with narrow and preferred prescribed step widths, normal walking, and walking with low-stiffness and high-stiffness stabilizers. Error bars indicate standard error of the mean.

$p = 0.52$; $\eta_p^2 = 0.02$; ΔRT_{prop}: $F_{4,152} = 0.24$, $p = 0.92$; $\eta_p^2 = 0.01$) were not significant.

The ANOVAs on gait parameters as obtained for unconstrained walking (Table 2) revealed significantly wider SW and shorter stride length in older adults than young adults. Stride length and stride time decreased with dual tasking, whereas cadence increased.

4. Discussion

We tested the assumption that the attentional costs of walking vary with lateral balance control requirements [13,14,20] in a head-on fashion. We hypothesized that lower balance demands (lateral stabilization) would reduce the attentional costs of walking, whereas higher balance demands (narrow base of support) would increase the attentional costs. These effects were expected to be more pronounced in older adults.

However, the obtained ΔRT measures were not influenced by lowered balance demands: walking with lateral stabilization did not result in lower ΔRT and ΔRT_{prop} compared to unconstrained walking, and neither did variations in stiffness of the stabilization device affect the ΔRT measures. Comparison between the two SW conditions (narrow vs. preferred) revealed no effect of increased balance demands on the attentional costs either, as the expected increase in ΔRT measures for the narrow SW condition was not observed. These results suggest that the contribution of balance control to attentional costs of walking was rather limited. Interestingly, however, the attentional costs increased when steps were adjusted to visual lines (i.e. in the prescribed SW conditions). In particular, the observed difference between unconstrained walking and walking on visual lines at the individual's preferred SW (i.e. the two conditions with comparable balance demands) indicated that the required visuomotor control in the latter situation resulted in elevated attentional demands. These results suggest that the attentional costs of walking depend more on visuomotor factors than on balance demands.

Our findings are not consistent with studies reporting variation of attentional costs with changes in balance requirements [9,10,13,14]. In those studies, base-of-support manipulations were used to vary balance demands (walking vs. standing or sitting; single-support vs. double-support stance phases), whereas in the present study the balance-demands manipulation was effectuated throughout the entire gait cycle. These differences hamper direct comparison with previous results.

The minor impact of lateral balance demands on attentional costs of walking may be related to the neurophysiological mechanisms underlying balance control. The presence of postural responses in decerebrated cats underscores the role of subcortical structures in mediating balance reactions, at least in mammals [21]. It has been suggested that this finding may be generalized to humans in view of a similar reliance of postural reactions on brain stem structures [22]. The subcortical nature of these mechanisms may explain why in our study lateral balance control during walking did not appear to affect higher-level cognitive processes associated with the RT task. In contrast, single-unit recording studies in animals showed more reliance on cortical activity (e.g., primary motor cortex) in locomotor tasks that are highly dependent on visuomotor processes, such as precision stepping [23]. Koenraadt et al. [24] reported increased activity in the prefrontal cortex in humans during walking on visual targets compared to unconstrained walking. As this area is typically involved in complex gait tasks that are attentionally demanding, such as walking while talking [25], this observation suggests that visually guided walking requires more attention than normal walking. Indeed, larger RTs have been

Table 2
Effects of group and single vs. dual tasking on gait parameters.

	Young adults		Older adults		Main effects		Interaction effect
	Single task[a]	Dual task[a]	Single task[a]	Dual task[a]	Group[b]	Task[b]	Group × Task[b]
Step width (m)	0.14 (0.03)	0.15 (0.04)	0.16 (0.02)	0.17 (0.02)	7.77 (**0.01**; 0.17)	2.40 (0.13; 0.06)	0.60 (0.44; 0.02)
Stride length (m)	1.28 (0.13)	1.25 (0.13)	1.12 (0.17)	1.11 (0.17)	9.99 (<**0.01**; 0.21)	28.73 (<**0.001**; 0.43)	2.87 (0.10; 0.07)
Stride time (s)	1.12 (0.10)	1.10 (0.09)	1.11 (0.12)	1.10 (0.14)	0.001 (0.97; 0.00)	16.46 (<**0.001**; 0.30)	0.54 (0.47; 0.01)
Cadence (steps/min)	108 (9)	110 (9)	109 (11)	111 (12)	0.04 (0.86; 0.001)	22.15 (<**0.001**; 0.34)	1.45 (0.24; 0.04)

[a] Values are presented as: mean (SD).
[b] Values are presented as: *F*-ratio (*p*-value; η_p^2). Significant *p*-values are presented in bold face.

reported for visually cued walking than for unconstrained walking [9,10], even if the unconstrained and visually imposed walking patterns were similar, indicating a relation between visuomotor demands and the attentional costs of walking [11,12].

Our hypothesis that variation of lateral balance demands has a more pronounced effect on attentional costs of walking in older adults was not supported either. This absence of a group by task interaction may be related to the primarily subcortical nature of postural control. The finding that also the elevated attentional demands in the two SW conditions (involving enhanced visuomotor control) did not differ between the groups may be associated with the fact that participants walked at their preferred walking speed, which was slower in older adults (see Table 1). Reduced walking speed may reflect a conservative strategy adopted by older adults to preserve their limited attentional resources (indicated by lower baseline RT; cf. Table 1) for other tasks. Recent studies reported slower self-selected walking speeds in visuolocomotor situations (e.g., walking on a narrow path [26] or a sequence of stepping stones [27]) compared to unconstrained walking, for young and older adults alike. This was interpreted as an adaptive strategy to favor task performance relative to the visual context [26,27]. Given our current results, it thus seems likely that older adults slowed down their preferred walking speed to increase the available time for visuolocomotor control [28,29].

Because the absence of significant effects may be associated with limited sample size, we conducted a post hoc power analysis for detecting a group by task interaction [30]. Given our sample size ($n = 40$), alpha level (0.05), and obtained interaction effect size (Cohen's $d = 0.14$), the power to detect such an effect was 0.09. The required sample size to obtain power at the recommended level of 0.80 was thus 636, which would be exceptionally large for an experimental study like this. Another limitation of the study may reside in the reduced ecological validity of treadmill walking, which may have increased attentional costs, introducing the potential risk of a ceiling effect obscuring differences between conditions. However, the pronounced elevation of ΔRT measures in the prescribed SW conditions indicates that treadmill walking as such did not induce a ceiling effect for attentional demands. Another limitation relates to our decision to present RT stimuli at heel strike, whereas the more attentionally demanding single-support stance phase may have been more sensitive to condition or group effects [14]. A final limitation is that dual-tasking effects on gait parameters were only examined for unconstrained walking. The RT task induced significant but small differences in stride length (2 cm), stride time (20 ms) and cadence (1 step/min), suggesting that the RT task had a limited effect on walking. This is consistent with other studies showing no [13,14] or negligible effects [9] of RT tasks on gait parameters under the instruction to prioritize the walking task. However, as we did not include single-task trials for the lateral-stabilization and imposed SW conditions (to limit the experiment's duration), it remains uncertain to what extent the prioritization instructions were successful in those experimental conditions.

In conclusion, our results indicate that, in healthy adults, attentional demands of walking were not influenced by variations in lateral balance demands. Perhaps the primarily subcortical nature of postural responses [21,22] requires minimal use of attentional resources. The higher attentional costs observed for walking on visual lines indicated that visuolocomotor demands contributed more to the attentional costs of walking than balance demands. The observation that the way in which ΔRT measures varied over conditions did not differ over the age groups may be associated with both the largely subcortical control of balance and the fact that both groups walked at their preferred walking speed (which was slower for older adults).

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Conflict of interest

None declared.

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