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RESEARCH ARTICLE

Walking in high-risk settings: Do older adults still prioritize gait when distracted by a cognitive task?

Sabine Schaefer · Michael Schellenbach · Ulman Lindenberger · Marjorie Woollacott

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Abstract When a cognitive and a motor task like walking or keeping one's balance are performed concurrently, performance usually deteriorates. Older adults have often been shown to prioritize their motor performance in such dual-task situations, possibly to protect themselves from falls. The current study investigates whether these prioritization behaviors can still be observed when several challenges are combined. Younger (20–30 years old) and older adults (60–70 years old; $n = 24$ in each group) were asked to walk through virtual environments with and without a cognitive load (3-back task). Walking difficulty was increased by walking on an elevated surface or on a narrow as opposed to a broad track, or both. Walking instructions emphasized speed and accuracy (avoiding missteps). No instruction was given concerning which performance dimension should be prioritized during dual-task trials. Participants decreased their 3-back performance while walking. Younger adults maintained their walking speed on elevated surfaces and were able to keep the number of missteps low, even when walking on a narrow track while performing the cognitive task. Older adults increased their walking speed on elevated relative to even surfaces and committed more missteps under cognitive load. Results suggest that task prioritization might fail in healthy older adults if several challenges are combined in high-risk settings.

Keywords Dual-task · Cognition · Walking · Threat · Aging

S. Schaefer (✉) · U. Lindenberger
Center for Lifespan Psychology, Max Planck Institute for Human Development, Lentzeallee 94, 14195 Berlin, Germany
e-mail: schaefer@mpib-berlin.mpg.de

M. Schellenbach
Computer Science Institute, University of Applied Sciences Ruhr West, 45407 Mülheim an der Ruhr, Germany

M. Woollacott
Department of Human Physiology, Institute of Neuroscience, University of Oregon, Eugene, OR 97403, USA

Introduction

Falls are an important public health concern, especially in the older adult population. The risk of falls in older adults increases with age, with 33 % of adults over the age of 65 falling per year (Hausdorff et al. 2001; Hornbrook et al. 1994). There is a significant correlation between falls history in older adults and performance in dual-task settings involving gait and a secondary cognitive task (Makizako et al. 2010). Although an easy cognitive task can sometimes lead to a more stable gait in certain environments for some populations, older adults dealing with a rather difficult cognitive task typically show gait deteriorations under dual-task conditions (e.g., Verrel et al. 2009), making it more likely to fall while attention is distracted by a secondary task.

Several previous studies have hypothesized that falls in older adults that occur in dual-task contexts may be associated with the inability to prioritize motor performance when allocating attention between the two tasks. The prioritization of postural control has been termed the "posture first strategy", and it can be applied to situations that challenge people's posture (LaJoie et al. 1993; Shumway-Cook et al. 1997; Shumway-Cook and Woollacott 2000) or gait (Li et al. 2001; Siu et al. 2008; Verghese et al. 2007). For example, older adults with balance impairments and a history of falls were not able to flexibly allocate attention between a postural task (walking over obstacles) and a secondary cognitive task, when asked to shift attention between the two tasks (Siu et al. 2008, 2009). When instructed to focus their attention on the gait task rather than the cognitive task, balance impaired older adults did not change their gait or secondary task performance characteristics.

In the study by Li et al. (2001), healthy older adults showed higher dual-task costs in the cognitive domain compared to younger adults. Dual-task costs were always calculated in relation to each individual's single-task performance, and the older adults had higher proportional costs in a word learning task than the young adults. However, the two age groups had comparable costs in their walking speed on a narrow track, even while crossing obstacles. The authors interpret this behavior as a prioritization of walking in order to reduce the risk of falls, but the specific conditions under which older adults fail to use the "posture first" strategy remain to be elucidated.

Inability to allocate attention to gait can be of increased importance in older adults when walking under conditions in which a risk of falls is more costly, in terms of risk of injury. This can occur, for example, when walking on narrow or elevated walkways. Research has shown that anxiety is often associated with walking under these conditions and is specifically related to the increased fear of falling (Brown et al. 2006; Delbaere et al. 2009; Hadjistavropoulos et al. 2012). Brown et al. (2006) have shown that both young and healthy older adults alter their gait when walking on elevated or narrow walkways in obstacle avoidance conditions, specifically by slowing gait velocity and reducing stride length, and thus are more efficient at negotiating obstacles on elevated walkways than they are on level ground. In a second study (Gage et al. 2003), they have shown that arousal, as measured by galvanic skin responses, was highest in the elevated narrow walkway condition.

Most of these studies on gait patterns in young and older adults in high-risk environments showed that healthy older adults can safely modify their gait in these settings to reduce fall risk; however, most of the experiments were only performed under single-task conditions, without any cognitive load. It is therefore important to investigate whether older adults can equally adjust their gait when walking under high-risk conditions, such as on elevated or narrow walkways, when performing a distracting secondary task (supporting the "posture first" hypothesis). These are essential aspects of balance and gait function, as a high percentage of gait tasks occurs in complex outdoor environments where many attentional distractors are present and thus present increased levels of fall risk. The study by Hadjistavropoulos et al. (2012) indicates that combining an environmental challenge and a dual-task situation leads to a less stable gait. They asked older participants to walk either on the floor or on an elevated platform and to carry a tray in the dual-task condition. When carrying the tray, people who were both fearful and at higher fall risk walked slower, took smaller steps, and showed increased gait variability.

In the current study, we examined these questions further by asking both younger and older adults to perform a simple (flat wide surface) versus higher-risk (elevated and/or narrow surface) gait task in a virtual reality setting. We compared their performance in the single-task setting (walking only) versus a dual-task setting with cognitive load (i.e., walking while performing a 3-back task). Virtual environments are increasingly used to test and train motor behaviors in older adults (e.g., Rendon et al. 2012). We made participants wear 3D goggles to make the virtual world appear more realistic. The most challenging virtual worlds of the current study were deliberately designed to be very difficult (i.e., walking on a narrow track on an elevated surface), since we wanted to investigate at which level of difficulty adaptive task-prioritization processes might fail. Dependent measures for walking were the walking speed, step width and the number of missteps on the narrow track. The misstep dimension is particularly important for investigating task-prioritization processes, since missteps would lead to falls in the real world, especially when walking on elevated surfaces. We hypothesized that younger adults would be able to flexibly alter their gait strategies in the higher-risk settings, by slowing gait speed and by reducing their step widths, to maintain a margin of safety in the gait task, resulting in few stepping errors on the narrow track, even in the dual-task setting. If the "posture first" hypothesis is supported by the walking behavior of healthy older adults, we would expect that they would also slow gait speed in this dual-task setting. At the same time, we expected that they would have more difficulty than younger adults maintaining a low number of missteps when attention is distracted in the dual-task context, reflecting age-related reductions in attentional resources.

Methods

Participants

We recruited 24 younger adults (20–30 years, $M = 25.75$, $SD = 2.17$) and 24 older adults (60–70 years, $M = 66.87$, $SD = 2.59$) from the participant pool of the MPI for Human Development and by distributing flyers. There were equal numbers of men and women in each age group. A telephone screening assured that participants who reported problems with their gait and balance (e.g., due to neurological disorders, attention-deficit-hyperactivity syndrome, brain tumors, orthopedic problems, or dizziness) were excluded from study participation. All participants had normal or corrected-to-normal vision and hearing. Perceptual speed (Digit-Symbol Substitution; Wechsler 1981),

Table 1 Participant characteristics

	Younger adults	Older adults	Difference between groups
Digit-symbol substitution (number of items)			$t(46) = 5.60$,
M	62.67	47.71	$p = .000$
SD	9.32	9.16	Young > old
MWT-A (number of items)			$t(46) = 3.05$,
M	31.04	32.92	$p = .004$
SD	2.05	2.21	Old > young
Number repetition (sum score of best forward and backward trial)			$t(46) = .03$,
M	13.96	13.63	$p = .763$
SD	3.57	4.02	Young = old
Body mass index (kg/m^2)			$t(46) = 2.10$,
M	23.33	25.17	$p = .041$
SD	2.96	3.10	Old > young
Fear of falling score (max = 100, no fear)			$t(46) = .59$,
M	96.98	96.31	$p = .556$
SD	.88	.69	Young = old

vocabulary (MWT-A; Lehrl et al. 1991) and memory span (number repetition; Wechsler 1981) were assessed to document cognitive age typicality of the sample. Table 1 presents the results separately by age group, including the direction and significance of age differences. The overall picture on the cognitive measures is consistent with the developmental literature showing that perceptual speed shows an early decline with aging, whereas verbal knowledge remains stable or even improves into later adulthood (e.g., Li et al. 2004). Age differences in body mass indices are in line with findings from representative studies (Hemmelmann et al. 2010). Participants were low in fear of falling as assessed with the Activities-specific Balance Confidence (ABC) scale (Powell and Myers 1995).

The Ethics Committee of the MPI for Human Development approved of the study. Participants received 70 Euro for their participation.

Apparatus

A 10-camera (infrared MX13+) Vicon motion capture system (Vicon MX, Nexus 1.4; Vicon Ltd, Oxford, UK), sampling at 100 Hz, was used for capturing participants' motion on the treadmill. Gym shoes in all sizes were prepared with reflective markers at the heel, over the fourth metatarsal joint, and over the second metatarsal head. Twelve reflective markers were placed on the following positions of each leg, according to the Plug-In Gait model: directly over the posterior–superior iliac spine, directly over the anterior–superior iliac spine, over the lower lateral 1/3 surface of the thigh, on the lateral epicondyle of the knee, on the tibial wand (over the lower 1/3 of the shank), on the ankle (on the lateral malleolus along an imaginary line that passes through the transmalleolar axis). A feedback-controlled program continuously analyzed the position and steps of the person on the treadmill and adapted the treadmill's speed accordingly (Czienskowski et al. 2008).

Participants walked on a treadmill (Woodway GmbH, Weil am Rhein, Germany) that had its walking area (200 × 70 cm) at the level of the surrounding floor. No handrail was present. In order to prevent complete falls, a safety harness was fastened around the waist of the participant and to the ceiling. The harness did not support the subject's body weight.

A 270 × 202 cm flat screen was mounted in front of the treadmill. Subject's distance to the screen varied depending on their walking speed and ranged roughly between 1 and 2.5 m. Depending on the experimental condition, one out of four different virtual environments was back-projected by a beamer onto the screen. The virtual environments had been programed in Ogre3D. Participants were wearing goggles in order to perceive the virtual environment in 3D. The room was dark except for the illuminated virtual world. The visual flow of the virtual environment was synchronized to the speed of the treadmill with an empirically established flow/speed ratio (see also Lövdén et al. 2005).

Experimental tasks

3-back

A series of 32 numbers ranging from 1 to 9 were presented via loudspeakers, with an average inter-stimulus-interval (ISI) of 2,250 ms. The ISIs were randomized between 2,000 and 2,500 ms to prevent periodic coordination of gait

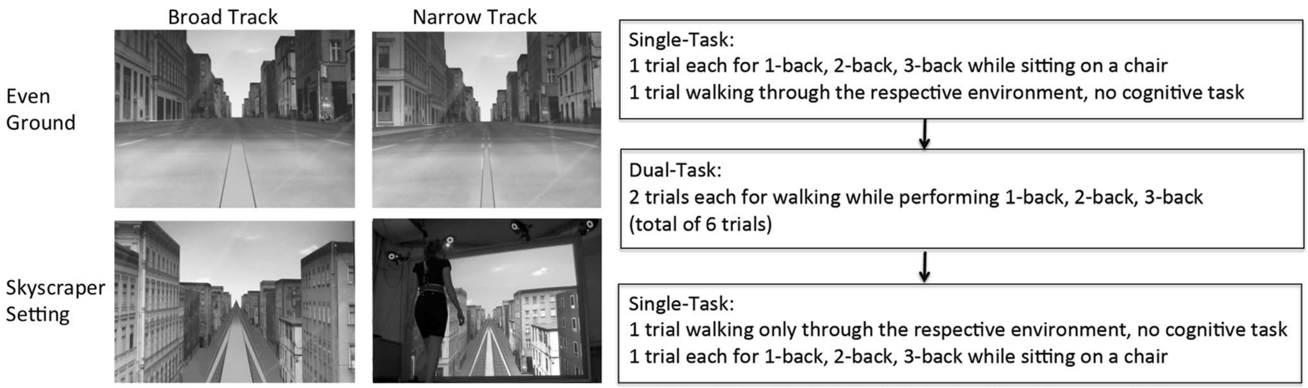

Fig. 1 The four different virtual environments and a flowchart of the experimental procedure in each session. The "narrow track in elevated setting" shows a person walking through the virtual world. The infrared cameras can bee seen on top of the screen

patterns with cognitive task performance. Participants were instructed to say "Tap" whenever the currently presented digit was identical to the digit presented three positions earlier (e.g., the bold digits of the following sequence are targets: 1 7 3 8 **7** 5 2 8 3 7 **8** 6…). There were seven target digits in each trial. Performance was measured by the number of correctly identified targets minus the number of false alarms. During testing, task-difficulty levels ranged from 1-back to 3-back, including 2-back. The present report focuses on the 3-back condition, since it is the only difficulty level in which participants consistently show no ceiling effects in their cognitive performance. Participants received performance feedback after each trial.

Walking

While walking on the treadmill, a virtual environment was projected onto the screen in front of participants. There were four different virtual environments: broad track on even ground, narrow track on even ground, broad track in elevated setting, and narrow track in elevated setting. Figure 1 presents the four different environments and a person walking through the "narrow track—elevated" environment. The general setting in each environment consisted of a street with houses on both sides. In the elevated setting, participants were walking on a track that was approximately 12 m (40 ft) above the ground. The broad track was 65 cm wide. The narrow tracks required that participants' feet remained within the boundaries of the virtual track, which was 20 cm wide. If they touched the virtual boundaries, the motion analysis system recorded the misstep and provided visual feedback by showing a red bar at the respective side of the track. Participants were instructed to walk on the treadmill "as fast as possible" on the broad tracks (where missteps could not be committed), and "as fast and as accurately as possible" on the narrow tracks. Dependent variables were the walking speed (m/s) and the number of missteps on the narrow tracks. Participants received performance feedback for all relevant dimensions after each trial.

Procedure

The study consisted of five sessions, which were performed on separate days. Each session lasted between 60 and 90 min. In the first session, participants signed the informed consent form, worked on the tests of the cognitive covariates and practiced the 3-back task. They also performed three 30-s trials walking in each virtual environment. Each environmental condition was assessed in one of the following sessions (sessions 2–5), and the order of environmental conditions was counterbalanced across participants. Each session started with a single-task block of *N*-back (while sitting on a chair), with one trial in each difficulty level (1-back to 3-back). The order of *N*-back difficulty levels (ascending versus descending) was also counterbalanced across sessions and participants. Participants then performed one trial of single-task walking in the respective environment, lasting for 76 s. The dual-task block assessed walking while concurrently performing the *N*-back task, with two 76-s trials in each difficulty level (1-back, 2-back, and 3-back; resulting in a total of six trials). Another trial of single-task walking and another block of *N*-back under single-task conditions (i.e., when sitting) was administered at the end of each session, to control for practice effects over the course of the session (see also Fig. 1).

In order to motivate participants to perform well on all three performance dimensions (*n*-back score, walking speed, and missteps on the narrow tracks), reinforcement points were administered throughout the dual-task sessions, rewarding participants with little gifts (e.g., sweets, books, vouchers for the cinema) if they performed successfully. Reinforcement points were randomized across conditions, and participants were not informed which dimension would be reinforced on a specific trial. No instruction was given concerning which performance dimension should be prioritized during dual-task trials.

Trials of the same condition were averaged for the analyses. Mixed-design ANOVAs were performed separately for the dependent variables (3-back performance, walking speed, missteps), with walking difficulty and cognitive load as within-subjects factors, and age group as between-subjects factor. For some analyses, the walking difficulty factor was further subdivided into walking height (even ground vs. elevated) and track width (broad vs. narrow track). For within-subject effects, the multivariate F values are reported. Significant interactions were followed up by t tests. In cases in which variances were not equal in t tests or in which the sphericity assumption was not met in mixed-design ANOVAs, corrected degrees of freedom have been used. The alpha level was .05 (Bonferroni corrected for follow-up t tests to .025).

Results

3-back

Figure 2 presents the results for the 3-back task. A mixed-design ANOVA with walking difficulty (5: sitting, walking broad even, walking broad elevated, walking narrow even, walking narrow elevated) as within-subjects factor and age group (2: younger vs. older adults) as between-subjects factor revealed significant differences in 3-back performance as a function of walking difficulty, $F(4, 184) = 3.00$, MSE $= .92$, $p < .05$, $\eta^2 = .061$, with decreases in performance when the virtual environment was more challenging. The interaction of this effect with age group did not reach significance, $F(4, 184) = 1.33$, MSE $= .92$, $p = .261$, $\eta^2 = .028$. Note, however, that the statistical power to detect an interaction effect was rather low (observed power $= .410$), and that inspection of Fig. 2 suggests that older adults reduced their cognitive performances more strongly with increasing walking difficulty than young adults.

The polynomial contrast concerning the shape of the relationship between walking difficulty and 3-back performance shows that it can best be described with a linear function ($p < .01$), indicating that performances decrease linearly with increasing difficulty of the walking task. All the other functions (quadratic, cubic, and fourth order) did not reach significance (all $ps > .170$). Furthermore, age group differences in 3-back performance did not reach significance, $F(1, 46) = 2.88$, MSE $= 5.75$, $p = .097$, $\eta^2 = .059$, indicating that younger and older adults performed at comparable levels.

Walking

Speed

Figure 3 presents the walking speeds of the two age groups in the four different virtual environments, while walking only as compared to walking while working on the 3-back task. A mixed-design ANOVA with walking height (2: even ground vs. elevated setting), track width (2: broad vs. narrow) and cognitive load (2) as within-subjects factors and age group (2: younger vs. older adults) as between-subjects factor revealed a significant main effect of walking height, $F(1, 46) = 8.22$, MSE $= .02$, $p < .01$, $\eta^2 = .152$, which

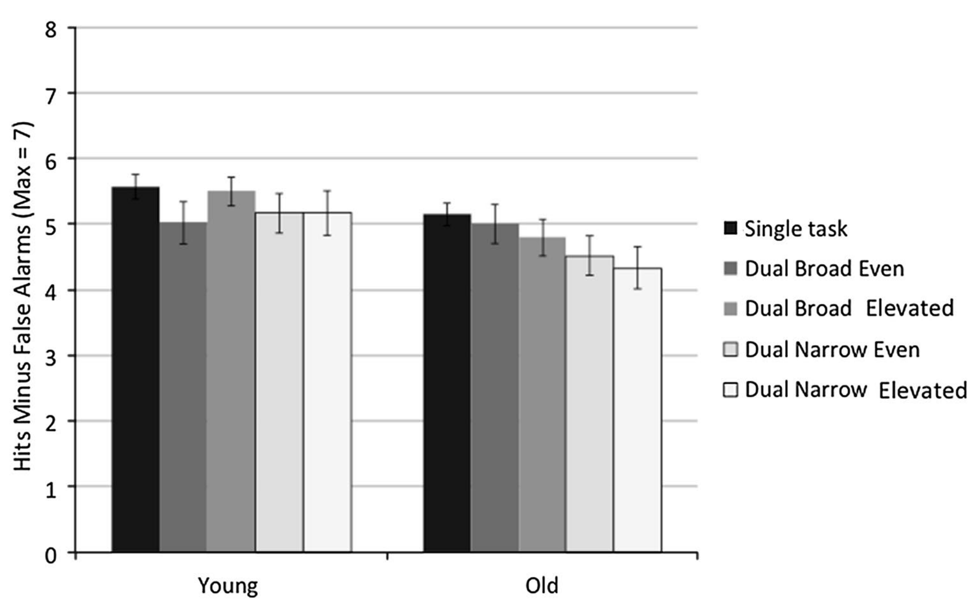

Fig. 2 Three-back performance while sitting (single task) or while walking in different virtual environments. Performance is measured by subtracting the number of false alarms from the number of correctly identified targets (hits). Both age groups reduce their cognitive performance when walking. *Error bars* SE mean

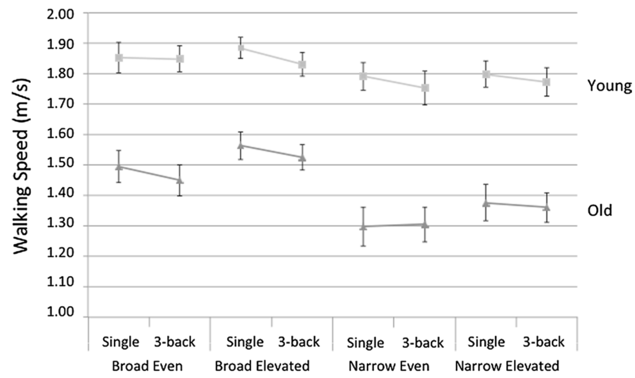

Fig. 3 Walking speed (m/s) in different virtual environments with and without cognitive load. Slowing down one's walking speed in challenging environments (elevated setting) can be considered adaptive. *Error bars* SE mean

interacted significantly with age group, $F(1, 46) = 4.49$, MSE $= .02$, $p < .05$, $\eta^2 = .089$. Surprisingly, walking in the elevated setting was even faster than on even ground, but the two age groups differed in how strongly walking speeds were influenced by the two settings. Follow-up dependent samples t tests revealed that younger adults did not show walking speed differences between even ground and elevated settings, $t\ (23) = -.69$; $p = .499$, while older adults showed significant differences, $t\ (23) = -2.97$; $p < .01$. Instead of slowing down, they sped up in the more demanding (and potentially threatening) environment.

The main effect of track width also reached significance, $F(1, 46) = 60.86$, MSE $= .02$, $p < .001$, $\eta^2 = .570$, indicating that walking speeds were reduced when walking on the narrow as opposed to the broad track, and this effect interacted significantly with age group, $F(1, 46) = 9.52$, MSE $= .02$, $p < .01$, $\eta^2 = .172$. To follow this up, dependent samples t tests comparing broad and narrow track walking were calculated for each age group separately. Walking speed reductions on the narrow track reached significance in each age group ($t\ (23) = 4.16$; $p < .001$, for younger adults, and $t\ (23) = 6.60$; $p < .001$ for older adults).

In the overall ANOVA, the main effect of cognitive load reached significance, $F(1, 46) = 6.13$, MSE $= .003$, $p < .05$, $\eta^2 = .118$, but it did not interact with age group, $F(1, 46) = .10$, MSE $= .003$, $p = .749$, $\eta^2 = .002$, indicating that the tendency to reduce walking speed when cognitively challenged did not differ reliably between younger and older adults. None of the possible two-way interactions of walking height, track width or cognitive load reached significance, and neither did the three-way interactions of these factors with age group (all ps $> .332$), or the four-way interaction of walking height, track width, cognitive load and age group ($p = .057$). Age groups differed in their mean walking speed, $F(1, 46) = 39.58$, MSE $= .37$, $p < .001$, $\eta^2 = .463$, with younger adults walking faster than older adults.

Step width

The narrow tracks required participants to adjust their step width to avoid missteps. A mixed-design ANOVA with track width (2: broad vs. narrow), walking height (2: even ground vs. elevated setting), and cognitive load (2) as within-subjects factors and age group (2: younger vs. older adults) as between-subjects factor revealed a significant main effect of track width ($F(1, 45) = 161.05$, MSE $= 10.10$, $p < .001$, $\eta^2 = .782$), which did not interact with age group ($F(1, 45) = .27$, MSE $= 10.10$, $p = .469$, $\eta^2 = .012$). The main effect of walking height did not reach significance ($F(1, 45) = .27$, MSE $= 1.15$, $p = .606$, $\eta^2 = .006$), but the interaction of walking height and age group was significant ($F(1, 45) = 12.62$, MSE $= 1.15$, $p < .01$, $\eta^2 = .219$), due to younger adults showing a decrease in step width on the elevated surface ($M = 4.38$ cm; SD $= 1.50$ cm) compared to the even ground ($M = 4.83$ cm; SD $= 1.70$ cm; $t\ (23) = 2.76$; $p < .025$), reflecting their ability to adjust their gait to task demands, while older adults showed an increase in step width on the elevated surface ($M = 6.85$ cm; SD $= 2.36$ cm) compared to even ground ($M = 6.45$ cm; SD $= 2.29$ cm; $t\ (23) = -2.56$; $p < .025$). Furthermore, the overall ANOVA revealed a significant main effect of cognitive load ($F(1, 45) = 49.83$, MSE $= .70$, $p < .001$, $\eta^2 = .525$), due to participants showing broader steps when cognitively challenged, and no interaction of cognitive load and age group ($F(1, 45) = 1.28$, MSE $= .70$, $p = .264$, $\eta^2 = .028$). The age groups differed significantly in their step width, with older adults showing broader steps than younger adults ($F(1, 45) = 14.69$, MSE $= 30.14$, $p < .001$, $\eta^2 = .246$). All other two-way, three-way, and the four-way interactions did not reach significance except for the interaction of track width, cognitive load, and age group, $p < .01$.

Missteps

Missteps indicated that the participants had stepped outside the virtual boundaries of the narrow track. Since missteps did not occur on the broad tracks, Fig. 4 presents the missteps on narrow tracks on even ground and in the elevated setting, with and without cognitive load.

A mixed-design ANOVA with walking height (2: even vs. elevated) and cognitive load (2) as within-subjects factors and age group (2: younger vs. older adults) as between-subjects factor was conducted. The main effect of walking height did not reach significance, $F(1, 46) = .69$, MSE $= 23.96$, $p = .412$, $\eta^2 = .015$, but there was a significant interaction of walking height and age group, $F(1, 46) = 6.06$, MSE $= 23.96$, $p < .05$, $\eta^2 = .116$, indicating that the age groups differed in the extent to which their missteps were influenced by environmental condition. The main effect of cognitive load reached significance as

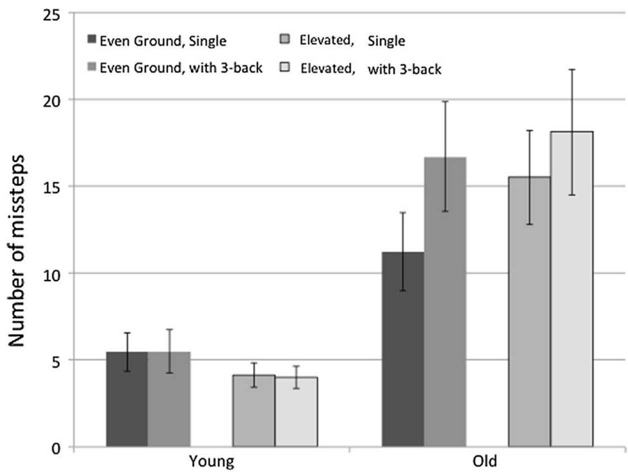

Fig. 4 Number of missteps on the narrow tracks on even ground and in the elevated setting, with and without cognitive load. *Error bars* SE mean

well, $F(1, 46) = 5.81$, MSE = 23.96, $p < .05$, $\eta^2 = .112$, with more missteps made under cognitive load. This effect interacted with age group, $F(1, 46) = 6.05$, MSE = 23.96, $p < .05$, $\eta^2 = .116$. The interaction of walking height and cognitive load as well as the three-way interaction of walking height, cognitive load, and age group did not reach significance (all *p*s > .287). Age groups differed in the number of missteps that were committed, $F(1, 46) = 14.38$, MSE = 23.96, $p < .001$, $\eta^2 = .238$, with younger adults committing fewer missteps than older adults.

To follow-up the significant interactions of walking height and age group as well as the interaction of cognitive load and age group, repeated measures ANOVAs with walking height (2) and cognitive load (2) as within-subjects factors were calculated for each age group separately. In younger adults, neither the main effect of walking height ($F(1, 23) = 2.08$, MSE = 23.17, $p = .163$, $\eta^2 = .083$) nor the main effect of cognitive load ($F(1, 23) = .01$, MSE = 6.40, $p = .936$, $\eta^2 = .000$) nor the interaction of these two factors ($F(1, 23) = .04$, MSE = 4.16, $p = .843$, $\eta^2 = .002$) reached significance. In older adults, there was a trend for walking height, $F(1, 23) = 3.98$, MSE = 49.09, $p = .058$, $\eta^2 = .148$, with more missteps in the elevated setting, and a significant effect of cognitive load, $F(1, 23) = 6.56$, MSE = 59.73, $p < .05$, $\eta^2 = .222$. The interaction of walking height and cognitive load did not reach significance ($F(1, 23) = 1.13$, MSE = 43.77, $p = .298$, $\eta^2 = .047$).

Correlations of misstep changes and speed changes

Do people who change their walking speed from even ground to elevated surface more strongly than others also show more pronounced changes in the number of missteps? And do young and older adults differ in that respect? Young adults showed a negative correlation of changes in walking speed on the narrow track from even to elevated surface and changes in missteps in the respective conditions (averaging across cognitive loads), $r = -.411$, $p < .05$, indicating that those who reduced their walking speed more strongly tended to increase the number of missteps. In older adults, however, there was no correlation, $r = .335$, $p = .110$.

Discussion

The current study investigated whether younger and older adults differ in their task-prioritization strategies when walking through virtual worlds with different levels of challenge, from walking on a flat and wide surface to walking on elevated and narrow surfaces. Older adults have been exposed to different walking settings in previous work (Li et al. 2001; Siu et al. 2008; Verghese et al. 2007), but to our knowledge, no study has systematically varied environmental and cognitive challenges in a virtual world in young and old adults. In addition, the fact that participants could slow down and speed up on the treadmill increases the ecological validity of the treadmill walking task compared to other age-comparative treadmill studies in which the speed of the treadmill did not change (Lövdén et al. 2005; Verrel et al., 2009). Walking on elevated and narrow surfaces presumably leads to a higher level of perceived threat and anxiety. Reducing one's walking speed in response to higher-risk environmental conditions, and reducing one's step widths to avoid missteps, especially when walking on elevated surfaces, is an adaptive strategy in this context. Younger adults actually demonstrated these behaviors, and they were also able to keep a rather low number of missteps on the narrow track when concurrently working on a cognitive task. However, there seem to be interindividual differences within the group of younger adults as well. The fact that those young adults who decreased their walking speed on the elevated surface also tended to commit more missteps might reflect anxiety-induced maladaptive gait alterations in some young participants, but further research on such tendencies is necessary.

Older adults, on the other hand, showed no consistent use of a "posture first" strategy: Although they slowed down their walking speed on the narrow track and under cognitive load, similar to young adults, their behavior on the elevated walkway can be considered problematic: Instead of slowing down on the elevated walkway, they sped up, causing an increase in the number of missteps. Older adults also committed more missteps on the narrow track under cognitive load as compared to no load. In the real world, missteps on elevated narrow walkways can lead to falls with potentially severe consequences. The speed increase in the threatening environment might be caused by the wish to escape this situation as fast a possible (i.e., participants want to "get it over with"). Such a form of escape behavior can be related to research on approach and avoidance motivation (e.g., Cain and LeDoux 2008).

It should be kept in mind that the older adults of the current study were physically very fit, given that persons with balance problems or any condition that rendered walking on the treadmill difficult had been excluded from study participation. In addition, the older adults did not report any fear of falling in their everyday life, as assessed by a standardized questionnaire on potentially threatening situations (Powell and Myers 1995). Nevertheless, they showed problematic task-prioritization behaviors when faced with the very demanding situation of walking on a narrow elevated walkway while performing a rather difficult cognitive task.

Our results contrast with findings reported by Brown et al. (2006) who asked younger and older participants to walk on even or elevated and on wide or narrow walkways while crossing virtual obstacles. Older adults showed a more conservative gait when walking on the elevated surface, leading to fewer obstacle contacts. However, there are studies showing that older adults make ineffective mobility decisions when a cognitive load is added, leading to more collisions with oncoming cars when crossing a virtual street while listening to music or by conversing on a phone (Nagamatsu et al. 2011). Falls may even occur in young and healthy adults if very demanding dual-task situations are used (Barra et al. 2006). In the current study, Fig. 4 shows that older adults committed significantly more missteps than younger adults in all of the conditions. This might indicate that the misstep dimension was too difficult for them in the first place, such that they might have given up on it entirely once they realized that they would not be able to perform without any errors. In order to render such a strategy less likely, future work with this paradigm could adjust the width of the walkway to each individual's performance level. Individually adjusting task difficulties is often done in age-comparative experimental research (see Brehmer et al. 2007; Li et al. 2001; Schaefer et al. 2008, for examples), with the aim to avoid floor or ceiling effects in specific age groups. But there are also disadvantages to this strategy: In real life, older adults (or children, respectively) have to climb stairs that are equally high for everybody, or process an announcement on the subway within a specific time frame, or adjust their posture to the same external perturbation during a bumpy bus ride. More might be learned about task prioritization in everyday life if participants of all age groups are confronted with exactly the same tasks, even if that means that some individuals are no longer able to perform them at all.

Concerning alternative interpretations of our findings, we cannot exclude the possibility that the prioritization of walking in older adults was reflected in a tendency to keep up or even increase walking speed at the expense of walking accuracy on the narrow tracks, since both dimensions were emphasized in the instruction. When walking on the broad tracks, where missteps could not occur, both age groups did reduce their walking speed under cognitive load. Only when several challenges were combined (i.e., walking on elevated narrow tracks under cognitive load) did the older adults show maladaptive strategies, by neglecting the misstep dimension, which would lead to falls in the real world. With respect to external validity, more severe consequences following missteps may influence the likelihood of their occurrence. If the trial is aborted after a specific number of missteps, even older adults might be able to strategically reduce the number of missteps at the expense of walking speed and cognitive performance. In a similar vein, instructing participants to focus more on one task dimension than on the other will show whether older adults are able to shift their task priorities at all in a specific dual-task setting. With the current design, it remains on open question whether older adults would have been able to prioritize the walking performance if explicitly instructed to do so. In a study with 9- and 11-year-old children who prioritized their posture when balancing on an ankle-disk board while performing a cognitive task, children continued to prioritize posture even when they were instructed to pay more attention to the cognitive task (Schaefer et al. 2008), probably because they were operating at their stability boundaries already. Siu and Woollacott (2007) furthermore demonstrated that young adults also do not sacrifice postural performance, even when instructed to focus on a visual-spatial memory task. Findings by Kelly et al. (2010) suggest that young adults are quite successful in shifting their attention between a walking task and a cognitive task, but that the extent to which attention can be shifted is influenced by the difficulty of the postural control task.

A potential limitation of the current study is the use of a virtual world instead of a real-world scenario. Participants were aware that real falls would not happen on the treadmill, and their task-prioritization strategies may therefore have been different from the real world. However, the use of virtual environments is well-established in research on dual-tasks involving posture and gait and in mobility training with the elderly (for examples, see Mirelman et al. 2011; Neider et al. 2011; Rendon et al. 2012; Yang et al. 2008), and 20 min of familiarization to treadmill walking in a virtual environment has been shown to be sufficient to reach stable walking patterns that closely resemble those observed in overground walking in young and old adults (Schellenbach et al. 2010). Virtual worlds are reported to elicit the feeling of being immersed, and they enable researchers to study situations that would be difficult or impossible to study in the real world due to the risk of harm or injury.

To conclude, the current study suggests that task-prioritization processes protecting the person from physical harm (“posture first” strategy) might break down in healthy older adults when faced with a demanding and potentially threatening situation. This implies that older adults should be aware of their limitations concerning which types of cognitive-motor dual-task situations they can safely handle in everyday life. Future research should elucidate the situations that are particularly problematic and investigate whether older adults can strategically influence their behavior when instructed to do so.

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Conflict of interest The authors declare no conflict of interest.

References

Barra J, Bray A, Sahni V, Golding JF, Gresty MA (2006) Increasing cognitive load with increasing balance challenge: recipe for catastrophe. Exp Brain Res 174:734–745. doi:10.1007/s00221-006-0519-2

Brehmer Y, Li S-C, Müller V, von Oertzen T, Lindenberger U (2007) Memory plasticity across the lifespan: uncovering children’s latent potential. Dev Psychol 43:465–478. doi:10.1037/0012-1649.43.2.465

Brown LA, Doan JB, McKenzie NC, Cooper SA (2006) Anxiety-mediated gait adaptations reduce errors of obstacle negotiation among younger and older adults: implications for fall risk. Gait Posture 24:418–423. doi:10.1016/j.gaitpost.2005.09.013

Cain CK, LeDoux JE (2008) Emotional processing and motivation: in search of brain mechanisms. In: Elliot AJ (ed) Handbook of approach and avoidance motivation. Psychology Press, New York, pp 17–34

Czienskowski P, Schellenbach M, Oertzen TV (2008) Feedback-controlled locomotion in virtual environments. In: Gulz A, Magnusson L, Malmborg H, Eftring H, Jönsson B, Tollmar K (eds) NordiCHI 2008: building bridges. ACM Press, New York, pp 447–450

Delbaere K, Sturnieks DL, Crombez G, Lord SR (2009) Concern about falls elicits changes in gait parameters in conditions of postural threat in older people. J Gerontol A Biol Sci Med Sci 64A:237–242. doi:10.1093/gerona/gln014

Gage WH, Sleik RJ, Polych MA, McKenzie NC, Brown LA (2003) The allocation of attention during locomotion is altered by anxiety. Exp Brain Res 150:385–394. doi:10.1007/s00221-003-1468-7

Hadjistavropoulos T, Carleton RN, Delbaere K et al (2012) The relationship between fear of falling and balance confidence with balance and dual tasking performance. Psychol Aging 27:1–13. doi:10.1037/a0024054

Hausdorff JM, Rios DA, Edelberg HK (2001) Gait variability and falls risk in community-living older adults: a 1-year prospective study. Arch Phys Med Rehabil 82:1050–1056. doi:10.1053/apmr.2001.24893

Hemmelmann C, Brose S, Vens M, Hebebrand J, Ziegler A (2010) Perzentilen des body-mass-index auch für 18-bis 80-Jährige? Daten der nationalen verzehrsstudie II. Dtsch Med Wochenschr 135:848–852. doi:10.1055/s-0030-1253666

Hornbrook MC, Stevens VJ, Wingfield DJ, Hollis JF, Greenlick MR, Ory MG (1994) Preventing falls among community-dwelling older persons: results from a randomized trial. Gerontologist 34:16–23. doi:10.1093/geront/34.1.16

Kelly VE, Janke AA, Shumway-Cook A (2010) Effects of instructed focus and task difficulty on concurrent walking and cognitive task performance in healthy young adults. Exp Brain Res 207:65–73. doi:10.1007/s00221-010-2429-6

Lajoie Y, Teasdale N, Bard C (1993) Attentional demands for static and dynamic equilibrium. Exp Brain Res 97:139–144. doi:10.1007/BF00228824

Lehrl S, Merz J, Burkhard G, Fischer S (1991) Manual zum MWT-A. Perimed Fachbuch Verlag, Erlangen

Li KZH, Lindenberger U, Freund AM, Baltes PB (2001) Walking while memorizing: age-related differences in compensatory behavior. Psychol Sci 12:230–237. doi:10.1111/1467-9280.00341

Li S-C, Lindenberger U, Hommel B, Aschersleben G, Prinz W, Baltes PB (2004) Transformations in the couplings among intellectual abilities and constituent cognitive processes across the life span. Psychol Sci 15:155–163. doi:10.1111/j.0956-7976.2004.01503003.x

Lövdén M, Schellenbach M, Grossman-Hutter B, Krüger A, Lindenberger U (2005) Environmental topography and postural control demands shape aging-associated decrements in spatial navigation performance. Psychol Aging 20:683–694. doi:10.1037/0882-7974.20.4.683

Makizako H, Furuna T, Shimada H, Ihira H, Kimura M, Uchiyama E, Oddsson LI (2010) Association between a history of falls and the ability to multi-task in community-dwelling older people. Aging-Clin Exp Res 22:427–432. doi:10.3275/6763

Mirelman A, Maidan I, Herman T, Deutsch JE, Giladi N, Hausdorff JM (2011) Virtual reality for gait training: can it induce motor learning to enhance complex walking and reduce fall risk in patients with Parkinson’s Disease? J Gerontol A Biol Sci Med Sci 66A:234–240. doi:10.1093/gerona/glq201

Nagamatsu LS, Voss M, Neider MB, Gaspar JG, Handy TC, Kramer AF, Liu-Ambrose TYL (2011) Increased cognitive load leads to impaired mobility decisions in seniors at risk for falls. Psychol Aging 26:253–259. doi:10.1037/a0022929

Neider M, Gaspar JG, McCarley JS, Crowell JA, Kaczmarski H, Kramer AF (2011) Walking and talking: dual-task effects on street crossing behavior in older adults. Psychol Aging 26:260–268. doi:10.0137/a0021566

Powell LE, Myers AM (1995) The activities-specific balance confidence (ABC) scale. J Gerontol A Biol Sci Med Sci 50:M28–M34. doi:10.1093/gerona/50A.1.M28

Rendon AA, Lohman EB, Thorpe D, Johnson EG, Medina E, Bradley B (2012) The effect of virtual reality gaming on dynamic balance in older adults. Age Ageing 41:549–552. doi:10.1093/ageing/afs053

Schaefer S, Krampe RT, Lindenberger U, Baltes PB (2008) Age differences between children and young adults in the dynamics of dual-task prioritization: body (balance) versus mind (memory). Dev Psychol 44:747–757. doi:10.1037/0012-1649.44.3.747

Schellenbach M, Lövdén M, Verrel J, Krüger A, Lindenberger U (2010) Adult age differences in familiarization to treadmill walking within virtual environments. Gait Posture 31:295–299. doi:10.1016/j.gaitpost.2009.11.008

Shumway-Cook A, Woollacott M (2000) Attentional demands and postural control: the effect of sensory context. J Gerontol A Biol Sci Med Sci 1:M10–M16

Shumway-Cook A, Woollacott M, Kerns KA, Baldwin M (1997) The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. J Gerontol A Biol Sci Med Sci 52A:M232–M240

Siu K-C, Woollacott MH (2007) Attentional demands of postural control: the ability to selectively allocate information-processing resources. Gait Posture 25:121–126. doi:10.1016/j.gaitpost.2006.02.002

Siu KC, Lugade V, Chou LS, van Donkelaar P, Woollacott MH (2008) Dual-task interference during obstacle clearance in healthy and balance-impaired older adults. Aging-Clin Exp Res 20:349–354

Siu K-C, Chou L-S, Mayr U, van Donkelaar P, Woollacott M (2009) Attentional mechanisms contributing to balance constraints during gait: the effect of balance impairments. Brain Res 1248:59–67. doi:10.1016/j.brainres.2008.10.078

Verghese J, Kuslansky G, Holtzer R, Katz M, Xue X, Buschke H, Pahor M (2007) Walking while talking: effect of task prioritization in the elderly. Arch Phys Med Rehabil 88:50–53. doi:10.1016/j.apmr.2006.10.007

Verrel J, Lövdén M, Schellenbach M, Schaefer S, Lindenberger U (2009) Interacting effects of cognitive load and adult age on the regularity of whole-body motion during treadmill walking. Psychol Aging 24:75–81. doi:10.1037/a0014272

Wechsler D (1981) Wechsler Adult Intelligence Scale—revised (WAIS-R). Psychological Corporation, New York

Yang Y-R, Tsai M-P, Chuang T-Y, Sung W-H, Wang R-Y (2008) Virtual reality-based training improves community ambulation in individuals with stroke: a randomized controlled trial. Gait Posture 28:201–206. doi:10.1016/j.gaitpost.2007.11.007