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Walking Variability and Working-Memory Load in Aging: A Dual-Process Account Relating Cognitive Control to Motor Control Performance

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Effects of cognitive activities on walking variability are poorly understood. We parametrically manipulated working-memory load by using an *n*-back task in 32 younger adults and 32 older adults walking on a treadmill at self-selected speed. We found no dual-task costs for cognitive performance. Stride-to-stride variability was lower when participants performed an easy working-memory task than when they walked without cognitive tasks. Increasing working-memory load from 1-back to 4-back produced decreasing variability of stride time and stride length in younger but not in older adults. Extending the 2006 dual-process account proposed by Huxhold, Li, Schmiedek, and Lindenberger, we conclude that normal aging alters the trade-off between the effects of focus of attention and resource competition on walking variability.

Key Words: Dual-task cost—Resource Competition—Walking variability.

THE association between walking variability and difficulty of concurrent cognitive activities in adulthood and aging is poorly understood, and empirical findings are scarce and mixed. Considering that age-related gait alterations are a leading cause of falls and accidental death among older adults (Rubenstein & Josephson, 2002) and that these alterations are accompanied by declines in several aspects of cognitive functioning (Lövdén & Lindenberger, 2005; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005; Schaie, 1996), this state of affairs is clearly unsatisfactory.

Huxhold, Li, Schmiedek, and Lindenberger (2006) recently suggested that a dual-process account might reconcile a similarly mixed pattern of findings observed in the domain of balance control while standing. First, cognitive activities of lower difficulty may promote an external focus of attention that allows the motor system to self-organize and smoothly execute movement. With an internal focus of attention (i.e., focus on the movement per se), top-down cognitive control (Miller & Cohen, 2001; O'Reilly, 2006) may interfere with the self-organizing dynamics of the motor system (Beilock, Bertenthal, McCoy, & Carr, 2004; Rowe, Friston, Frackowiak, & Passingham, 2002; Wulf & Prinz, 2001). Second, higher levels of cognitive task difficulty may hamper motor control performance through cross-domain resource competition (Li, Lindenberger, Freund, & Baltes, 2001; Lindenberger, Marsiske, & Baltes, 2000; Schaefer, Huxhold, & Lindenberger, 2006; Woollacott & Shumway-Cook, 2002). The point at which performance improvements that are due to the first process is surpassed by decrements induced by the second process is assumed to be predictable from the individual's sensorimotor and cognitive resources in interaction with the tasks.

The two processes described may produce a U-shaped relation between motor control and difficulty of concurrent cognitive activities: Motor control is improved by cognitive tasks with low difficulty and diminished by additional increases in difficulty (Deviterne, Gauchard, Jamet, Vancon, & Perrin, 2005; Huxhold et al., 2006; Riley, Baker, & Schmit, 2003; Vuillerme, Nougier, & Teasdale, 2000). Huxhold and colleagues provided support for the viability of the dual-process account and the predicted U-shape pattern in the domain of maintaining a stable upright posture. Specifically, younger and older adults swayed less when concurrently performing an easy cognitive task (monitoring digits) than they did in a single-task baseline in which attention was directed to the postural control task. With more demanding cognitive tasks (choice reaction time and 2-back working-memory tasks), older adults increased sway whereas younger adults did not. Thus, the transition from decreases in sway to increases in sway occurred at lower task difficulty for older adults, presumably as a result of age-related increases in the demands of sensorimotor functions for cognitive control (i.e., less automaticity), age-related reductions in cognitive control efficiency, or both. In the present study, we address the dual-process account in the domain of walking and in the context of aging.

Our choice of the concurrent cognitive task and the variables describing walking behavior were primarily guided by the dual-process account. For the cognitive domain, we target working-memory (WM) processes, which relate to maintaining information in an active state while updating this information and influencing lower level processing streams (Engle, 2002; Miller & Cohen, 2001; O'Reilly, 2006). In other words, WM capacity is isomorphic with the top-down cognitive (or, attentional–executive) control processes putatively involved in producing the hypothesized U-shaped relationship between motor control performance and concurrent cognitive task difficulty. To manipulate WM load, we use the "*n*-back" task (Dobbs & Rule, 1989). This task is attractive because WM load can easily be manipulated parametrically.

Our description of walking behavior focuses on the stride-to-stride variability of gait parameters (velocity, step width, stride time, and stride length) obtained during treadmill walking at self-selected speed. Stride-time and stride-length variability are related to motor control of the rhythmic gait patterning (Gabell & Nayak, 1984); step-width variability relates to balance control (Gabell & Nayak); and variability of velocity may be conceived of as a global variability indicator. We assume that variability is a better indicator of the degree of dynamic self-organization of the motor system than the central tendency. For example, in many types of motor control tasks, high variability often indicates involvement of attention and cognitive control, whereas low variability indicates processes that proceed with little attention (Newell & Corcos, 1993). Moreover, step-time and step-width variability predict falls among older adults (Brach, Berlin, VanSwearingen, Newman, & Studenski, 2005; Hausdorff, Rios, & Edelberg, 2001; Maki, 1997). Thus, stride-to-stride fluctuations tap into important facets of motor control, the involvement of top-down cognitive control, and stability during walking (Hausdorff, 2005).

The evidence concerning adult age differences in the magnitude of fluctuations in stride-related gait parameters (e.g., stride length; stride time) is mixed. Some studies report higher variability among healthy older adults than among younger adults (e.g., Menz, Lord, & Fitzpatrick, 2003; Owings & Grabiner, 2004), but null findings have been reported as well (e.g., Gabell & Nayak, 1984; Hausdorff, Edelberg, Mitchell, Goldberger, & Wei, 1997). Cognitive load might be a moderator of age differences in variability. Beauchet and colleagues (2003) reported that variability of stride length and stride velocity, obtained from walking at preferred speed on a walkway, increased significantly for older adults when they concurrently performed a counting task. No significant effects of the counting task were observed for younger adults (see also Beauchet, Dubost, Herrmann, & Kressig, 2005). However, Grabiner and Troy (2005) reported that concurrent cognitive load (Stroop task) reduced step-width variability during walking at self-selected speed on a treadmill for younger adults. Hollman, Salamon, and Priest (2004) reported that variability of stride velocity was greater for older women than for younger women while the women were counting backwards and walking at preferred speed on a walkway, but not while walking without a cognitive task. Springer and colleagues (2006) reported that younger adults, older adults, and older adults with a history of recent falls decreased gait speed when performing a cognitive task, but only older adults with a fall history increased swing time variability.

In summary, age differences in stride-to-stride variability increase with concurrent cognitive load, potentially reflecting what has been coined the aging-related permeation of sensorimotor functions with cognition (Lindenberger et al., 2000; see Schaefer et al., 2006 and Woollacott & Shumway-Cook, 2002 for reviews). In other words, the motor control of walking requires cognitive involvement in old age. In young adulthood, walking might be relatively independently organized by the motor system. In line with this notion, Hausdorff, Yogev, Springer, Simon, and Giladi (2005) reported that between-person differences in catch-game performance (requiring movement planning, estimation, and real-time adjustment), but not tapping performance, were correlated with stride-time variability in a group of older adults. In addition, the study revealed that lower stride-time variability was associated with Stroop performance (a measure of cognitive control) but not with verbal memory performance, again pointing toward increased cognitive control demands of walking in normal aging.

The findings on effects of concurrent cognitive activities on stride-to-stride variability are corroborated by evidence concerning dual-task walking in general. For example, in a study by Lövdén, Schellenbach, Grossman-Hutter, Krüger, & Lindenberger (2005), younger and older men performed a way-finding task in virtual mazelike museums while walking on a treadmill with (holding on to a handrail) or without support. Walking support attenuated age-related decrements in navigation performance. In sum, mounting evidence indicates that the demands for cognitive control of walking increase in old age and that cognitive control efficiency decreases. This state of the art contrasts with the discrepant evidence, reconciled with the U-shape hypothesis (Huxhold et al., 2006), in the domain of postural control in balance, in which both positive (Deviterne et al., 2005) and negative (Vuillerme et al., 2000) effects of cognitive load have been observed. Thus, measures of balance control while standing might be more open to effects of an external focus of attention than indicators of control of walking. However, note that reductions of walking variability that are due to cognitive load have been observed for groups of younger adults (Grabiner & Troy, 2005).

In this study we examine the viability of the dual-process account in the domain of walking. To this end, we parametrically manipulate WM load for younger and older adults walking on a treadmill at their preferred speed, which we established while they were walking without a cognitive task. We predict that walking variability is related in a U-shaped manner to WM load and that the turning point of the function occurs at a lower nominal WM load for older adults than for younger adults, as a result of age-related decrements in sensorimotor and cognitive resources and increased coupling between their constituent processes.

METHODS

Participants

Our sample of 32 younger adults ($M_{\text{age}} = 25.0$ years; $SD_{\text{age}} = 2.9$ years; 16 women and 16 men) and 32 older adults ($M_{\text{age}} = 73.6$ years; $SD_{\text{age}} = 2.9$ years; 16 women and 16 men) came from the participant pool of the Max Planck Institute for Human Development, Berlin, Germany. Exclusion criteria included Parkinson's disease, diabetes, gout, rheumatism, severe back pain, disturbance of cardiac rhythm, dizziness, any type of self-reported impaired balance, history of heart attack or stroke, pain while walking, artificial hip joint, use of walking aids, or anything else restricting participants' normal gait. The age groups did not significantly differ ($p > .59$) with respect to history of falling, indicating a healthy sample of elderly participants. All participants had normal or corrected-to-normal vision and hearing.

We assessed perceptual speed (Digit-Symbol Substitution Test; Wechsler, 1982) and vocabulary (Mehrfachwahl-Wortschatz-Intelligenztest, Part A; Lehrl, Merz, Burkard, & Fischer, 1991) to document the cognitive age typicality of the sample. Older adults performed worse than younger adults in perceptual speed, $t(62) = 6.71$, $p < .001$, but better in vocabulary, $t(62) = 2.17$, $p < .04$. Thus, the sample

Table 1. Mean Spatiotemporal Gait Parameters in the 1-Back Condition and Anthropometric Data as a Function of Age Group

	Younger Adults		Older Adults	
Parameter	*M*	*SD*	*M*	*SD*
Velocity (m/s)	3.74	0.40	3.13	0.47
Stride time (ms)	1189.4	83.0	1203.1	126.0
Stride length (mm)	1227.9	103.0	1035.6	133.4
Step width (mm)	78.2	33.3	84.8	38.4
Height (cm)	177.6	9.8	169.4	10.0
Mass (kg)	71.6	13.1	74.3	11.5
Leg length (cm)	95.2	6.1	92.4	6.7

Note: *SD* = standard deviation.

approximates the population in displaying the typical developmental dissociation of fluid (perceptual speed) and crystallized (vocabulary) intelligence (Lövdén & Lindenberger, 2005). Mean estimates of a selection of spatiotemporal gait parameters obtained from the easiest (1-back) WM load condition and anthropometric data are displayed as a function of age group in Table 1. These means are fairly typical for groups of healthy young and old individuals.

Participants provided written consent prior to the experiment and received 50 Euro for their participation. The study was approved by the ethics committee of the Max Planck Institute for Human Development and conducted in compliance with the declaration of Helsinki.

Apparatus

We used a 12-camera (infrared V-cam 100 & 200) Vicon motion-capture system (Vicon 612, Workstation 4.6; Vicon Ltd., Oxford, UK), sampling at 200 Hz, for capturing participants' motion on the treadmill. Participants walked in gym shoes provided by our lab. The shoes in all sizes were prepared with one reflector marker at the head of the second toe and one at the heel.

Participants walked on a treadmill (Woodway GmbH, Weil am Rhein, Germany), with the walking area (200 × 70 cm) at the level of the surrounding floor. No handrail was present. For safety reasons, we had a harness fastened around the waist of each participant and to the ceiling.

We mounted a 200 × 270 cm screen in front of the treadmill. A virtual environment consisting of a straight path was backprojected to the screen (175 × 234 cm). We synchronized the visual flow of the virtual environment to the speed of the treadmill with an empirically established flow-to-speed ratio (Lövdén et al., 2005). The reason for projecting the virtual environment was to reduce the risk that participants unnaturally focused on the experimental environment while avoiding fixation at one point in space.

Procedure

Data collection consisted of two sessions. One session involved slow walking at 2.5 km per hour and one involved walking at self-selected speed. We counterbalanced the order of sessions. We obtained anthropometric data (e.g., height, weight) in the beginning of the first session. We assessed cognitive ability measures in the beginning of the second session. We tested participants individually in sessions that lasted approximately 2 hours. Here we consider only the session involving self-selected speed.

The session started with a familiarization phase. First, participants walked for 7 minutes at velocities varied upon participants' requests. Next, and after a complete stop, participants gradually increased velocity to determine preferred walking speed: this was a tempo allowing natural rhythmic walking with which they felt comfortable and that constituted "their own tempo with which they would walk when taking a walk in a park." Finally, participants walked at their self-selected speed for 3 minutes and were asked again if they felt comfortable with their choice. We used the selected speed for all subsequent trials.

The half of the sample starting with the preferred speed session was, at the time of selecting their preferred speed, unaware of the fact that a more cognitively demanding walking situation (walking with a cognitive task) was coming. The other half of the sample knew because of the previous encounter with the *n*-back task while walking. There were no differences in selected preferred speed between these two groups ($ps > .13$). Thus, there were no indications that selection of walking speed was influenced by awareness about the upcoming cognitively demanding walking situation. Our preliminary analyses of effects of session order on the walking measures (see the paragraphs that follow) revealed no significant interactions with the main factors of interest. We therefore collapsed the order factor.

The next phase of the session started and ended with assessment of 1-back to 4-back performance while the participants were sitting comfortably in a chair and a 1-minute walking trial without any concurrent cognitive task. In between these trials, participants completed trials of walking while concurrently performing the *n*-back task. The experimenter provided no specific instructions for how the participants should walk.

The *n*-back tasks involved series of 26 digits from 1 to 9 presented over loudspeakers. Depending on the (1-back to 4-back) condition of WM load, participants were instructed to verbally respond with "yes" whenever a digit was heard that was the same as presented one, two, three, or four positions back in the series. The experimenter noted all responses and later scored them as correct or false alarms. The interstimulus interval varied randomly between 2,350 and 3,150 ms to prevent rhythmical influences on gait. To avoid articulation during the motion capture, none of the six target items occurred in the 20-second interval in which motion was captured (always between Item 13 and Item 21).

For the walking trials, two trials for each load condition (1-back to 4-back condition) were completed in a row. For each of these trials, the participant walked for 30 seconds at preferred speed before the *n*-back task started. Motion was captured after another 30 seconds for 20 seconds. The task was completed after an additional 15 seconds. The participant was not aware of these time frames. The experimenter allowed the participants to take a 2-minute rest between the load conditions. We counterbalanced the order of difficulty of the *n*-back task (ascending or descending order of 1-back to 4-back condition).

Data Processing and Statistical Analyses

We postprocessed the motion data (heel and toe markers) in MATLAB 6.5 (Mathworks, Sherborn, MA). From the 20 seconds of motion data from each trial, we discarded the first and last 2.5 seconds as a result of unreliable data. From the remaining 15 seconds, we extracted nine gait cycles for all individuals. We computed the mean and standard deviation of stride time, stride length, and step width over the 18 steps separately for the left and right foot and the two trials of each condition. Subsequently, we averaged the estimates for left and right foot and the two trials of each condition. We replaced a few ($<3\%$) outliers (± 3 *SD*) by the values of the complementary trial within the same condition.

Stride-to-stride variability is typically either indicated by the within-person standard deviation (e.g., Grabiner, Biswas, & Grabiner, 2001) or the coefficient of variation (standard deviation divided by mean; see, e.g., Beauchet et al., 2003). Because our central hypothesis involves an interaction between age and WM load, rather than main effects of age, the need for normalizing to the mean is not prominent; particularly because an Age × WM Load interaction for the estimates of the mean spatiotemporal gait parameters was neither predicted nor empirically found. In order to stay closer to the raw data and avoid relying on the normalization assumptions involved in computing the coefficient of variation (e.g., mean has priority over variability), the main dependent variables in the walking domain were the within-person standard deviation of velocity, stride time, stride length, and step width. For WM performance, the dependent variable is the number of hits minus the number false alarms. With the exception of WM performance in the 1-back condition, which suffered from restricted variance caused by ceiling effects, the dependent variables displayed acceptable distributions (all skewness < 2.3; kurtosis < 6.0).

We performed mixed analyses of variance (ANOVAs) separately for the dependent variables. For the sensorimotor variables, we conducted two separate ANOVAs. A 2 (age group; younger or older]) × 2 (gender) × 2 (task; no load – 1 back) ANOVA addressed the effects of walking with no load as compared with a low load. A 2 (age group; younger or older]) × 2 (gender) × 4 (WM load; 1 back – 4 back) ANOVA addressed the parametric effects of WM load. WM load and task were within-subject factors. For WM performance, we performed a 2 (age group; younger or older) × 2 (gender) × 2 (setting; sitting or walking) × 4 (WM load; 1 back to 4 back) ANOVA. WM load and setting were within-subject factors. For within-subject effects, the multivariate *F* values are reported. The alpha level was .05 and the effect size statistic is a partial eta squared (η^2).

RESULTS

Working-Memory Performance

The ANOVA revealed significant main effects of age, $F(1, 60) = 26.81$, $p < .05$, $\eta^2 = .31$, and WM load, $F(3, 58) = 88.17$, $p < .05$, $\eta^2 = .82$. Figure 1 shows that younger adults performed better than older adults and that performance was worse under higher WM load for both age groups. These main effects were qualified by a significant Age × WM Load interaction, $F(3, 58) = 11.83$, $p < .05$, $\eta^2 = .38$, indicating that the effects of WM load were greater for older adults: Younger adults perform at ceiling in 1-back and 2-back conditions whereas older adults perform at ceiling only in the 1-back condition. No effects involving setting (sitting vs walking) were significant (all *p*s $> .12$). The absence of dual-task effects (i.e., effects of setting) in the cognitive domain indicates that effects of dual tasking in the sensorimotor domain can be interpreted without simultaneously considering effects in the cognitive domain. In other words, performance trade-offs between domains, or age differences therein, need not to be considered when one is interpreting the findings in the sensorimotor domain.

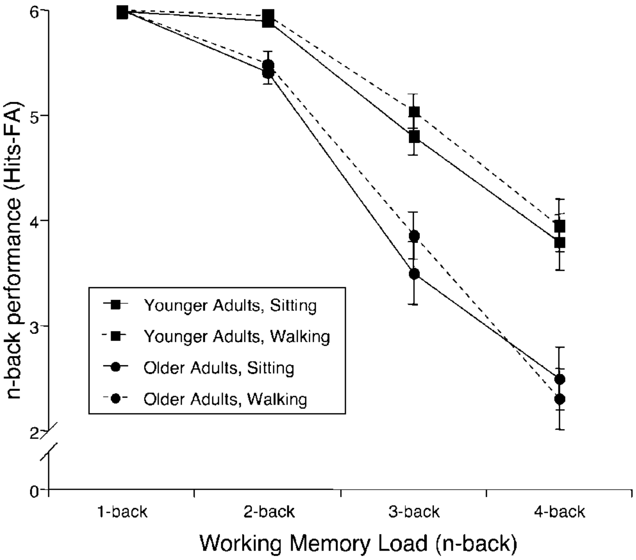

Figure 1. Mean (standard error) of working-memory performance (hits minus false alarms, or FAs) as a function of age group, working-memory load (*n*-back condition), and setting (sitting or walking).

Mean Estimates of Spatiotemporal Gait Parameters

We first report the statistical analyses addressing the effects of task (walking with no load as compared with a 1-back condition). There were significant main effects of age group in mean velocity, $F(1, 60) = 30.57$, $p < .05$, $\eta^2 = .34$, and stride length, $F(1, 60) = 46.74$, $p < .05$, $\eta^2 = .44$. Younger adults walked faster and with longer strides (see Table 1). For stride length, the Age × Gender interaction was significant, $F(1, 60) = 4.84$, $p < .05$, $\eta^2 = .08$, indicating age differences in stride length that were smaller for women.

The ANOVAs addressing the effects of parametrically manipulating WM load (1-back to 4-back condition) confirmed the aforementioned results. There were significant main effects of age group in velocity, $F(1, 60) = 30.79$, $p < .05$, $\eta^2 = .34$, and stride length, $F(1, 60) = 43.68$, $p < .05$, $\eta^2 = .42$. For stride length, the Age Group × Gender interaction was significant, $F(1, 60) = 4.94$, $p < .05$, $\eta^2 = .08$, indicating smaller age differences for women. In addition, a significant effect of WM load emerged in stride time, $F(3, 58) = 2.93$, $p < .05$, $\eta^2 = .13$, indicating increases in mean stride time with higher WM load.

In sum, younger adults walked faster and with longer strides than did older adults. Age differences in stride length were less pronounced for women. Average stride time increased with higher WM load. None of the Age × WM load interactions reached significance.

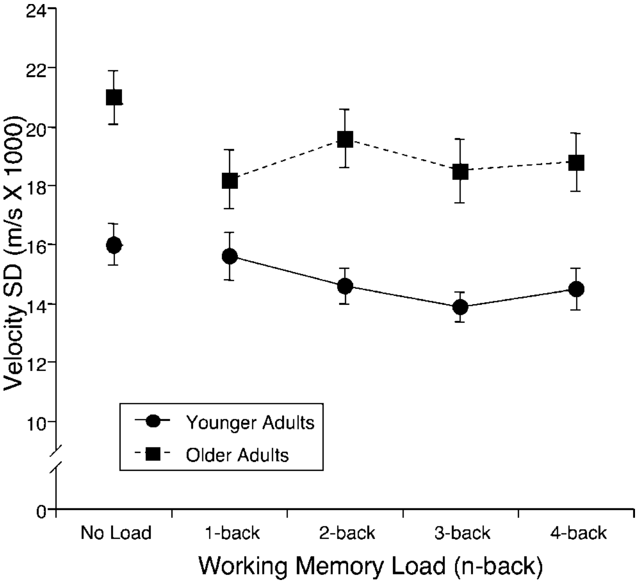

Figure 2. Mean (standard error) of stride-to-stride velocity variability (standard deviation) as a function of age group and working-memory load (no-load or *n*-back condition).

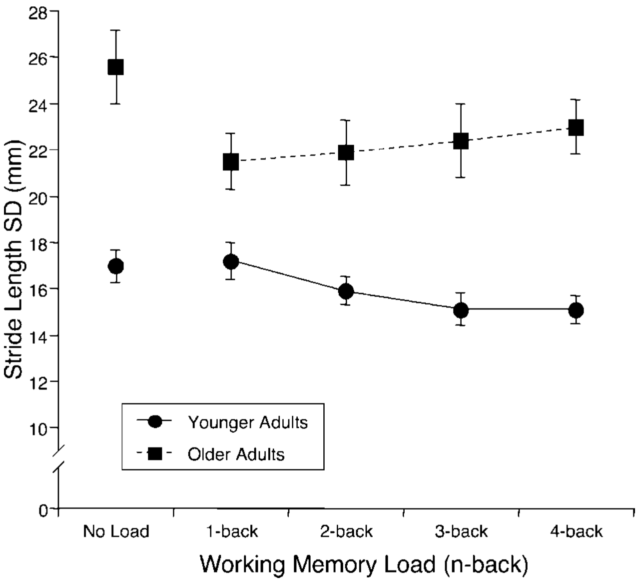

Figure 4. Mean (standard error) of stride-to-stride stride-length variability (standard deviation) as a function of age group and working-memory load (no-load or *n*-back condition).

Variability Estimates of Spatiotemporal Gait Parameters

The ANOVAs targeting the effects of having a cognitive task or not while walking (no load vs with a 1-back condition) yielded main effects of age for variability of velocity, $F(1, 60) = 14.72$, $p < .05$, $\eta^2 = .20$, stride time, $F(1, 60) = 7.41$, $p < .05$, $\eta^2 = .11$, and stride length, $F(1, 60) = 24.40$, $p < .05$, $\eta^2 = .29$. Older adults varied more than young adults in velocity (Figure 2), stride time (Figure 3), and stride length (Figure 4). The main effects of task were significant for velocity, $F(1, 60) = 7.18$, $p < .05$, $\eta^2 = .11$, stride length, $F(1, 60) = 5.70$, $p < .05$, $\eta^2 = .09$, and step width (Figure 5), $F(1, 60) = 9.02$, $p < .05$, $\eta^2 = .13$. Within-person variability was higher in the no-load condition than in the 1-back condition. For stride-length variability, there was a main effect of gender, $F(1, 60) = 5.47$, $p < .05$, $\eta^2 = .08$, indicating less variability for women than for men. The Age Group × Task interaction was significant for variability of velocity, $F(1, 60) = 5.78$, $p < .05$, $\eta^2 = .09$, and stride length,

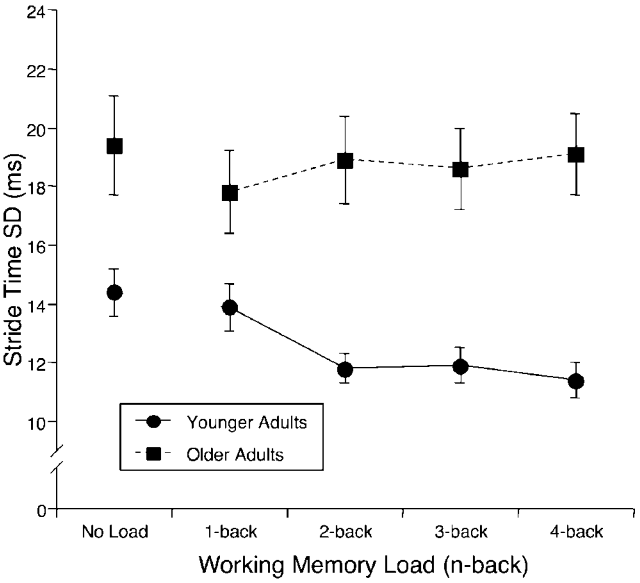

Figure 3. Mean (standard error) of stride-to-stride stride-time variability (standard deviation) as a function of age group and working-memory load (no-load or *n*-back condition).

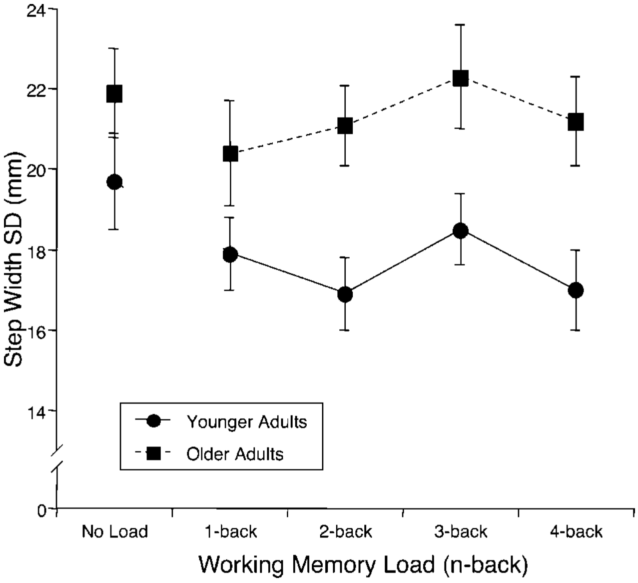

Figure 5. Mean (standard error) of stride-to-stride step-width variability (standard deviation) as a function of age group and working-memory load (no-load or *n*-back condition).

$F(1, 60) = 7.48$, $p < .05$, $\eta^2 = .11$, indicating statistical significant differences in variability of velocity [Figure 2; $t(31) = 3.48$, $p < .05$] and stride length [Figure 4; $t(31) = 2.86$, $p < .05$] between the no-load and 1-back conditions for the elderly adults but not for the younger adults [$t(31) = 0.21$, $p > .83$ for velocity and $t(31) = 0.40$, $p > .68$ for stride length].

The ANOVAs addressing the effects of WM load (1-back to 4-back condition) revealed main effects of age for all four dependent variables: velocity, $F(1, 60) = 17.83$, $p < .05$, $\eta^2 = .23$, stride time, $F(1, 60) = 18.35$, $p < .05$, $\eta^2 = .23$, stride length, $F(1, 60) = 29.51$, $p < .05$, $\eta^2 = .33$, and step width $F(1, 60) = 8.17$, $p < .05$, $\eta^2 = .12$. Older adults were more variable. The main effects of WM load were not significant. The Age × WM Load interaction was significant for stride-time variability, $F(3, 58) = 5.63$, $p < .05$, $\eta^2 = .22$, and stride-length variability, $F(3, 58) = 2.81$, $p < .05$, $\eta^2 = .13$. Inspection of Figure 3 (stride time) and Figure 4 (stride length) suggests that older adults maintain (or increase) stride-time and stride-length variability with higher WM load, whereas younger adults decrease variability with higher WM load. A one-way (WM load) ANOVA involving data from the younger adults showed a significant effect of WM load for stride time, $F(3, 29) = 5.52$, $p < .05$, $\eta^2 = .36$, and a marginally significant effect for stride length, $F(3, 29) = 2.91$, $p < .051$, $\eta^2 = .23$. The linear contrasts were significant for both variability of stride time, $F(1, 31) = 16.79$, $p < .05$, and stride length, $F(1, 31) = 8.70$, $p < .05$. Thus, the linear contrasts accounted for unique variance in these variability measures, which is consistent with a continuous decrease in variability. The quadratic contrast explained unique variance for stride time only, $F(1, 31) = 4.47$, $p < .05$, indicating a leveling out of the decrease. No such effects were revealed for the group of older adults (ps $> .27$).

Discussion

Huxhold and colleagues (2006) suggested that cognitive activities of lower difficulty induce an external focus of attention that allows the motor system to self-organize and therefore more smoothly execute movement than that which would be possible with a focus on movement per se (see also Beilock et al., 2004; Rowe et al., 2002; Wulf & Prinz, 2001). In contrast, higher levels of cognitive task difficulty may impede motor control performance through cross-domain resource competition (Lindenberger et al., 2000; Schaefer et al., 2006; Woollacott & Shumway-Cook, 2002). The turning point at which performance improvements that are due to the first process either levels off by itself or is superseded by performance decrements induced by the second process is assumed to depend on the demands of sensorimotor processes on cognitive control and the cognitive resources of the individual.

The present results suggest that this dual-process account is also applicable to walking. Specifically, our findings suggest a turning point for reductions in stride-to-stride variability at the 1-back condition for older adults, whereas these reductions continue to the 4-back condition for younger adults. Importantly, the continuous decrease in variability for younger adults indicates that the distinction between internal and external focus is gradual: Concurrent cognitive tasks of lower difficulty leave more cognitive capacity, or time, over for processes directed to the movement per se than cognitive tasks of higher difficulty that occupy most of the available resources most of the time. The finding of stronger decreases in variability from the no-load to 1-back conditions for older as compared with younger adults is in line with this reasoning. Specifically, at lower nominal levels of task difficulty (1-back condition), older adults' cognitive resources might be nearly exhausted by the WM task and continued increases in difficulty cannot further redirect the cognitive control processes from the movement. In contrast, younger adults might still have resources available at higher levels of nominal difficulty. The interaction of age and WM load on WM performance supports this interpretation (see Figure 1).

Given the absence of significant increases in walking variability as a function of WM load in old age, the present data do not rule out a single-process account, as they do not provide firm evidence that cross-domain resource competition occurs. A single-process account would have to assume that cognitive control resources available for an internal focus are depleted or redirected from an internal focus at lower levels of cognitive task difficulty in older than in younger adults. The failure to detect a negative effect of higher WM load in the old adults is clearly both inconsistent with theory and incompatible with past research: Processes of cross-domain resource competition in older adults' walking behavior have massive empirical support (Hausdorff et al., 2005; Lindenberger et al., 2000; Lövdén et al., 2005; Schaefer et al., 2006; Woollacott & Shumway-Cook, 2002). For example, older adults show greater reductions in walking speed and memory performance than do younger adults under dual-task conditions (Lindenberger et al.) and older adults' balance performance is impaired by higher levels of cognitive load (Huxhold et al., 2006). Therefore, we argue that walking in younger adulthood is, at least under less challenging conditions, a relatively automatic process. In contrast, walking variability in old adulthood is moderated both by focus of attention and by a process involving demands of the motor system on cognitive control accompanied by decreases in cognitive control efficiency.

The dual-process notion of two processes trading off has the potential to explain the mixed pattern of previous findings concerning dual-task walking and stride-to-stride variability, and failures to detect negative effects of cross-domain resource competition in this and past studies. Specifically, the postulated two processes may trade off in different ways and to different extents to produce associations between cognitive load and walking variability that are linearly decreasing, linearly increasing, or quadratic. Among the potentially many factors involved, cognitive task difficulty and the individual's resources may determine the nature of this association.

To exemplify, the effects of age on stride-length variability (Figure 4) is greater in the no-load and 4-back conditions than in the other *n*-back conditions. If only these extreme conditions were examined (i.e., no parametric design), we would have failed to detect an Age Group × Cognitive Load interaction. Thus, previous mixed findings of both increases (e.g., Beauchet et al., 2003) and decreases (e.g., Grabiner & Troy, 2005) of variability as a function of cognitive load could be explained by different cognitive task difficulties in interaction with the individual's cognitive and sensorimotor resources (which are associated with adult age), producing different trade-offs between dual processes. Such trade-offs may also explain why some studies, including ours, have failed to find a negative effect of cognitive load on sensorimotor performance in older adults. Specifically, the beneficial effects of cognitive load caused by an externalizing focus of attention may overshadow the negative effects of cross-domain resource competition. Such trade-offs may produce the present results for the older adults, that is, a quadratic relationship between walking variability and WM load but no significant increase in walking variability. Note, however, that the present results reveal a small tendency for increases in variability as function of higher WM load in older adults. Thus, care should be taken so that this null finding is not overinterpreted. Improved power or more sophisticated analyses of walking behavior may produce a stronger finding. Clearly, to precisely describe the dynamics and trade-offs among the two processes, and the environmental conditions determining these, is an important challenge for the dual-process account.

This study has several strengths but also some limitations. To the strengths belong the parametric manipulation of WM load and the use of variability as a measure of walking behavior. The procedural details including a treadmill at the level of the floor accompanied by a displayed virtual world and an extensive familiarization phase should enhance the ecological validity of this study as compared with several previous studies. However, despite these attempts to enhance validity, we highlight that findings observed for treadmill walking may not necessarily generalize to normal overground walking. Clearly, examining the generalizability of the dual-process account to different cognitive and sensorimotor situations should be on the research agenda. To the limitations of the study also belong the short motion captures underlying the within-person variability variables. Though no bias is expected, variability estimates based on a few gait cycles is likely to suffer from low reliability and therefore produce low statistical power (Owings & Grabiner, 2003). Thus, null findings should be interpreted with caution. Finally, we note that WM load and age differences in effects of WM load might be confounded with arousal level. Though our data cannot directly eliminate this alternative explanation, we are unable to find any convincing empirical evidence for an arousal explanation of the effects of cognitive activity on motor control during walking. For example, dual-task balance studies investigating the effects of cognitive demands on indicators of arousal, such as skin conductance, deliver mixed results of increases (Maki & McIlroy, 1996), decreases (Dault, Yardley, & Frank, 2003), and no changes (Maki & McIlroy) in arousal as a result of cognitive load. Thus, we refrain from an arousal explanation of the current findings.

To conclude, younger adults display a continuous beneficial effect of increasing WM load on interstride variability, indicating a gradual and beneficial effect of a process involving shifts to an external focus of attention. For older adults, walking variability levels off at lower nominal difficulty of concurrent WM load, presumably indicating a trade-off between dual processes: focus of attention and cross-domain resource competition. In other words, motor control of walking in younger adulthood is a relatively automatic process whereas control of walking in old age requires involvement of cognitive control processes.

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