GeroPsych, 23 (2), 2010, 69–77

Technology in Healthy Aging

Sensorimotor-Cognitive Couplings in the Context of Assistive Spatial Navigation for Older Adults

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Abstract. With advancing adult age, sensorimotor functioning, spatial processing, and the motivation to explore new environments decline, leading to impaired spatial navigation skills. Using a controlled virtual-world laboratory equipped with a treadmill interface, we examined how assistive navigation technologies differing in cognitive demand affect walking regularity and navigation performance in younger and older adults. Relative to an assistive device with low cognitive demands, older, but not younger adults' navigation performance decreased with a cognitively more demanding device. Furthermore, older adults showed higher gait irregularity than younger adults, especially with the cognitively demanding device. We conclude that assistive navigation devices show promise in supporting older adults' pedestrian mobility if aging-induced increments in cognitive demands of spatial navigation and postural control are considered.

Keywords: aging, technology, assistive technology, spatial navigation, sensorimotor functioning

Recent years have seen increasing efforts to improve and increase assistive technology for the aging population (Charness & Schaie, 2003; Fisk, Rogers, Charness, Czaja, & Sharit, 2004; LoPresti, Mihailidis, & Kirsch, 2004). However, technological and psychological inquiries have rarely been merged. Based on the selection, optimization, and compensation (SOC) model of successful psychological development (Baltes & Baltes, 1980; Riediger, Li, & Lindenberger, 2006), Lindenberger, Lövdén, Schellenbach, Li, and Krüger (2008; Lindenberger, 2007; Lindenberger & Lövdén, 2006) specified three criteria for the use of assistive technology: net resource release, person specificity, and proximal vs. distal frames of evaluation. In this paper we focus on the net resource release criterion in the domain of mobile navigational support, and use this criterion to arrive at implications for the design and concept of mobile assistive devices.

The use of assistive technology generally requires an investment of sensory/sensorimotor and cognitive resources. Here, the concept of net resource release underscores that the use of assistive technology is only adaptive when its use requires fewer resources than it releases so that the marginal resource gain associated with selecting assistive technology is positive (see Dixon & Bäckman, 1995). To enhance the likelihood of marginal resource gains, assistive technology design has to incorporate knowledge about negative adult age changes beyond the target activity, such as spatial navigation, and consider a broader set of domains, such as sensorimotor and cognitive functions. To illustrate this point, imagine an older adult visiting a big city and using a pedestrian mobile navigational device to find a particular museum. The system not only calculates the shortest route to the museum but also provides additional information about the city while supporting the route-finding task. As the person is so engaged in processing both the route and additional information, his or her focus of attention is distracted away from maintaining balance while walking, an activity that is known to require increasing attentional resources with advancing adult age (Li, Lindenberger, Freund, & Baltes, 2001; Lindenberger, Marsiske, & Baltes, 2000; Lövdén, Schellenbach, Grossman-Hutter, Krüger, & Lindenberger, 2005). Hence, by engaging cognitive resources, the mobile navigation system may destabilize walking performance, thereby contributing to the risk of falling.

Nevertheless, spatial navigation aids may show promise for improving older adults' declining spatial navigation performance if the cognitive demands used for their operation are not too high. Negative adult age differences in spatial processing, in general, and spatial navigation, in particular,

DOI 10.1024/1662-9647/a000010

are large and normative (Lövdén et al., 2005; Moffat, Zonderman, & Resnick, 2001). In the visuospatial domain, age-related impairments are large in mental rotation and visualization (Salthouse & Mitchell, 1989) and in spatial memory (Light & Zelinski, 1983). Age differences in these types of tasks are more palpable than in comparable verbal tasks (Jenkins, Myerson, Joerding, & Hale, 2000). Furthermore, assessment of route-learning skills provides support for substantial age-related deficits (Lipman, 1991; Lövdén et al., 2005; Moffat et al., 2001). Similarly marked deficits can be observed for tasks requiring spatial inferences of direction relations and distances between locations, such as in supermarkets (Kirasic, 2000).

Correlational studies and dual-task experiments point to an increase in sensorimotor-cognitive couplings from early to late adulthood (see Schäfer, Huxhold, & Lindenberger, 2006, for review). When cognitive and sensorimotor tasks are performed simultaneously, older adults show greater dual-task costs than younger adults in cognitive (Li et al., 2001), sensorimotor (Huxhold, Li, Schmiedek, & Lindenberger, 2006), or both domains (Lindenberger et al., 2000). In line with these findings, attempts at enhancing cognition by providing basic forms of sensory or sensorimotor support can be surprisingly effective. An example from our own laboratory illustrates this claim. Lövdén and colleagues (2005) projected maze-like virtual museums onto a screen located in front of a treadmill and then asked 16 20–30-year-old and 16 60–70-year-old men to perform a way-finding task in several of these virtual museums while walking on the treadmill. The task was to find the way from the entrance of the museum to the museum's bistro twice in a row without committing any errors (i.e., without taking wrong turns at intersections). In a condition of sensorimotor support, participants were allowed to hold on to a handrail. In a no-support condition, participants were asked to walk freely on the treadmill. Young adults' navigation performance was not affected by walking support. However, it took older adults considerably less time and walking distance to learn how to get through the virtual museum when gait control was aided by the handrail support. This finding supports the proposition that older adults need to invest increasing amounts of cognitive resources into sensorimotor aspects of behavior. It follows from this proposition that walking support not only improves postural control but also frees up cognitive resources that can then be invested into navigation-related processing (see also Li et al., 2001; Lindenberger et al., 2000).

Based on these considerations, the central hypothesis of this study is that assistive devices aimed at alleviating the cognitive resource load of spatial navigation may, like more basic forms of sensorimotor support, have positive effects on walking stability in addition to ameliorating way-finding performance. However, this positive effect should only be observed if the use of these devices results in a positive net resource release. Here, we tested this hypothesis by manipulating the putative cognitive demands of navigation aids from low to high and observing the effects of this manipulation on navigation performance and walking behavior in a laboratory virtual environment (VE) equipped with a treadmill (Schellenbach, Krüger, Lövdén, & Lindenberger, 2007). The low-demand aid condition was operationally defined by allowing participants to follow a red line (*virtual guide*) in the environment (e.g., much like way-finding lines provided in hospitals). In the high-demand condition, we displayed an *overview map* (e.g., similar to commonly used city maps) on the projection screen. A *no-support* condition was included as well.

The VE laboratory allowed navigational support to be included immediately in the (virtual) environment and enabled a precise analysis of the gait patterns. Walking irregularity, based on principal component analysis (PCA) of individual gait patterns (Verrel, Lövdén, Schellenbach, Schaefer, & Lindenberger, 2009), served as our main dependent variable for walking behavior. Using PCA, kinematic walking data were split into a main (regular) and a residual (irregular) pattern. Walking irregularity was quantified by the residual variance, that is, the relative amount of variance in the residual pattern (for details, see Verrel et al., 2009). As an additional measure of participants' movement characteristics, we also assessed the variability of participants' positional shift (right-left, anterior-posterior) on the treadmill, which is not captured by the PCA. By taking temporally continuous information relating to whole-body coordination into account, this approach may yield a more efficient and valid index of cognitive load-induced changes in whole-body coordination than step-related measures (see also Verrel et al., 2009).

In accordance with the well-documented decline of sensorimotor and cognitive functions (Lindenberger & Baltes, 1994; Park, Collins, & Turvey, 2001; Spirduso, Francis, Eakin, & Stanford, 2005) and closer coupling between these domains with advancing adult age (Baltes & Lindenberger, 1997; Lindenberger et al., 2000; Lövdén et al., 2005), the older participants were expected to show larger effects of the navigation aid manipulation on whole-body coordination while walking than younger adults. Thus, we predicted that the gait patterns of the older participants would be more regular in the *virtual-guide* (red line) condition than in the *no-support* condition, because of lowered cognitive demands in the *virtual-guide* condition. Likewise, we predicted that the gait patterns of the older participants would be less regular in the *overview-map* condition than in the *no-support* condition because utilizing the map would be cognitively more demanding than walking without the map. In contrast, we expected that the younger adults would not vary in gait regularity as a function of the type of assistive device. Further, we predicted better navigation performance in the support conditions compared to the nonsupported trials for both age groups, indicating the beneficial effect of navigation aid on navigation performance. Because of the higher cognitive demands required for utilizing the *overview map* as opposed to following the *virtual guide*, we again predicted better performance for the older adults in the guided condition but no significant differences for the younger adults.

Methods

Participants

We recruited 18 younger men (*M* = 24.4 years; *SD* = 1.9; age range: 21–28) and 18 older men (*M* = 72.3 years; *SD* = 3.0; age range: 68–77) from the participant pool of the Max Planck Institute for Human Development, Berlin, Germany. We excluded individuals with conditions known to influence balance or gait performance (Parkinson's disease, diabetes, gout, severe back pain, impaired balance, cardiovascular problems, hip replacement, and other self-reported conditions that might impair normal gait). All participants had normal or corrected-to-normal vision and hearing. In addition, all participants had already used a treadmill. Also, the age groups did not differ significantly with respect to experiencing serious falls in the past. Written consent was obtained from the participants prior to the experiment. Each participant received 60 Euros for participating in the entire experiment. The ethics committee of the Max Planck Institute for Human Development approved the study.

To document the sample's cognitive performance, Table 1 summarizes the scores on tests of visuospatial ability (mental rotation), perceptual speed (Digit Letter substitution), and verbal knowledge (Spot-a-Word) as a function of age group. The mental rotation tests were taken from Vandenberg and Kuse (Vandenberg & Kuse, 1978) and adapted for this study. Detailed descriptions of the other tests are provided by Lindenberger, Mayr, and Kliegl (1993; see also Lövdén, Ghisletta, & Lindenberger, 2004). The two mental rotations tests were combined into a single unit-weighted composite, and the variables were scaled in a T-metric (*M* = 50; *SD* = 10). An inspection of Table 1 suggests that younger adults performed better than older adults on the visuospatial and perceptual-speed measures, whereas older adults performed better than younger adults on the test of verbal knowledge. Univariate one-way (age group) analyses of variances (ANOVAs) for each composite confirmed these observations: visuospatial, $F(1, 34) = 26.93$, $p < .001$; perceptual speed, $F(1, 34) = 24.62$, $p < .001$; and verbal knowledge, $F(1, 34) = 10.68$, $p = .002$. Thus, the typical development pattern of age-related decreases in fluid abilities and age-related increases (or maintenance) in crystallized abilities was observed (see Lövdén & Lindenberger, 2005, for review). We conclude that the sample constituted a satisfactory approximation of the population trends for cognitive functioning.

Table 1. Cognitive characteristics and balance abilities as a function of age group

	Younger		Older	
Variable	*M*	*SD*	*M*	*SD*
Visuospatial ability	56.6	9.2	43.4	5.6
Perceptual speed	56.4	9.3	43.6	5.8
Verbal knowledge	45.2	11.8	54.8	4.2
Timed up and go (s)	6.9	1.4	8.8	1.9
Functional reach (cm)	41.2	6.4	35.7	6.5

Note. Visuospatial ability = T-scaled mean of Vanderberg-Kuse mental rotations test (Vandenberg & Kuse, 1978); perceptual speed = Digit Letters (items correct); Verbal knowledge = Spot-a-word (items correct).

Individual differences in sensorimotor functioning were assessed with the Timed Up and Go test (Podsiadlo & Richardson, 1991) and the Functional Reach test (Duncan, Weiner, Chandler, & Studenski, 1990). Means and standard deviations as a function of age groups are also included in Table 1. Almost all participants reached the highest level of balance ability (< 10 s in the Timed Up and Go test and > 25.4 cm for the Functional Reach test). Only one older man required 14.4 s for the Timed Up and Go test, while another scored 21.0 cm on average in the Functional Reach test. Both were assigned to the second highest level of balance (of four). Thus, none of the participants had significant balance difficulties, which is likely the result of a positive selection bias for the older age group, operating against our hypotheses.

Apparatus

We used an 11-camera (MX13) Vicon motion-capture system (Vicon MX hardware and Vicon Nexus 1.1; Vicon Ltd, Oxford, UK) sampling at 200 Hz to record participants' limb movements. Reflective markers were placed on relevant anatomical landmarks according to the VICON Plug-in-Gait Model.

Data were captured when participants walked on a motorized treadmill (Woodway GmbH, Weil am Rhein, Germany), with the walking area (200 cm × 70 cm) at floor-level. No handrail was present. A harness was put around the waist of the participant and attached to the ceiling for safety reasons. A 200 cm × 270 cm screen was mounted in front of the treadmill. Figure 1 shows a participant walking on the treadmill.

Six maze-like topographies representing virtual zoos were randomly generated according to the following con-

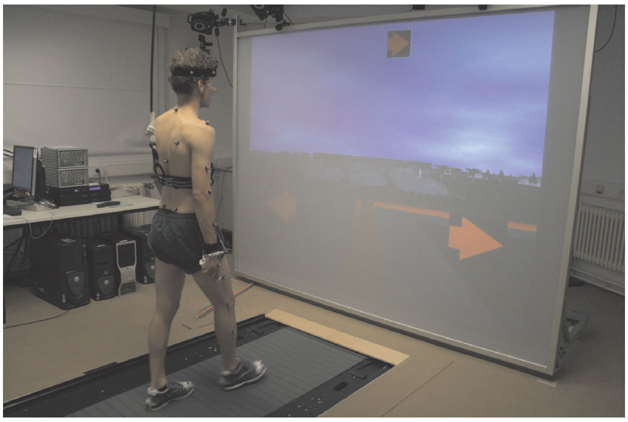

Figure 1. Participant navigating in one of the virtual zoos supported by the virtual guide.

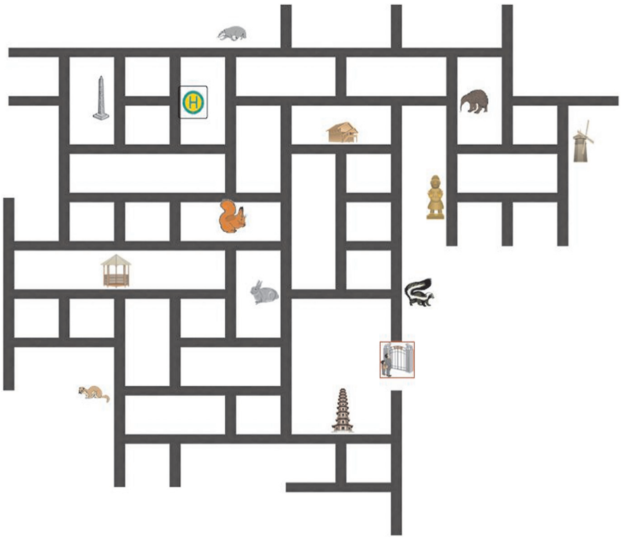

Figure 2. An example of the topographies used in the experiment.

straints: (a) Each maze consisted of eight decision points located on the direct route from the starting point to the goal; (b) all decision points were two-choice alternatives; (c) the same decision (i.e., right or left) on the direct route was only allowed to occur twice in a row; (d) all routes from the start to a dead end involved at least eight decision points. Each maze was constructed according to a *city block* layout (straight paths and 90 degree turns at decision points). Six different virtual zoos were constructed corresponding to six different maze-like topographies. Different, unique animals were placed on each first, third and sixth intersection (i.e., decision point) on the shortest route from the start to the goal. In addition, six unique objects were distributed as landmarks at other intersections in the zoo. The goal was symbolized using a unique bus-stop sign. Figure 2 illustrates these different features viewed from above. A smaller version of these mazes was used for the practice trials.

Two buttons were used for navigation in the virtual environment. The crossings were always two-choice intersections (left/right, left/straight, and straight/right). This means that participants performed a right click at a left/straight-intersection in order to go straight ahead. To order to minimize confusion for this specific interaction, it was also possible to skip this click to walk straight on. The speed of the treadmill was set individually to the preferred speed of the participants as defined in the familiarization phase. The movement within the virtual environment was set to a constant of 3.5 km/h, which represented a reasonable average speed based on other experiments with the same age groups. The benefit of this compromise was that it allowed every participant to walk at his preferred speed, without creating any disadvantage in terms of the time spent exploring the virtual environment. This was important to avoid fatigue influences for older adults in their navigation performance as well as in their gait pattern. The average walking speed in the present experiment was 3.82 km/h (*SD* = 0.61 km/h) for the younger adults and 3.24 km/h (*SD* = 0.72 km/h) for the older adults. Therefore, the fixed virtual speed successfully approximated the average walking speeds of both groups.

Design and Procedure

The study followed a 3 (Navigation support) × 2 (Age group) mixed design, with a sample size of 18 per age group and navigation support as a within-subjects factor. Three different support modes were used (see Figure 3): (a) *no support*, (b) *virtual guide* (red line), and (c) *overview map*. The main dependent variables of this study were walking variability and navigation performance based on distance covered to reach the goal. Navigational support was manipulated within subjects and two maze-learning tasks were carried out in each condition. For the *virtual-guide* condition and the *overview-map* condition, the supporting information was explained before the trial. Participants were required to use the additional information presented within the VE in the way-finding task. In the *no-support* condition, the participants had to explore the environment by themselves to find the goal.

The experiment consisted of three sessions with a one-day break between sessions. In the first session, partici-

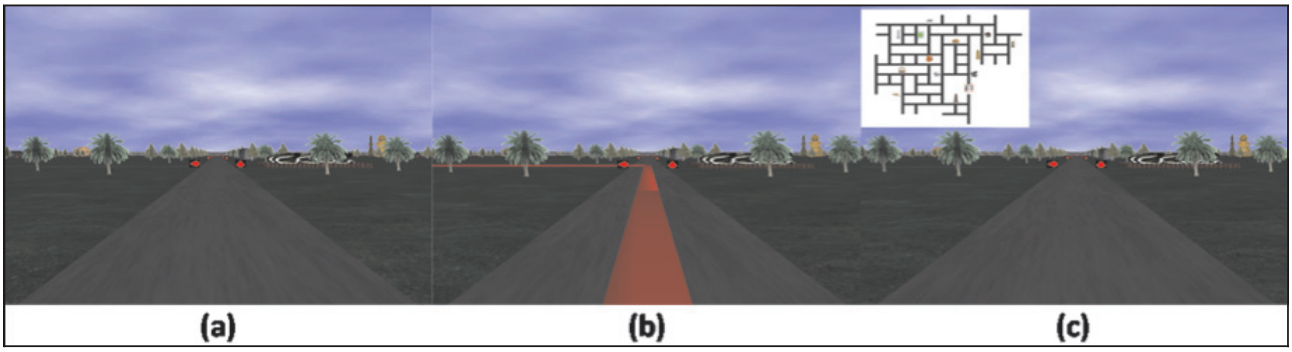

Figure 3. The user perspective while walking on the treadmill with (a) *no support*, (b) the *virtual guide* (red line), and (c) the *overview map*.

pants were interviewed and tested for a number of background variables after signing an informed-consent form. They then performed the Timed Up and Go task and the Functional Reach test. The second part of the session was spent on familiarizing participants with treadmill walking and finding a comfortable speed for the experimental sessions. In this part, different walking speeds were demonstrated before the experimenter increased the speed smoothly until the participant reached his comfortable speed. After 5 and 10 min of walking the participant again had the chance to alter his preferred speed. In each of the two following sessions, participants were asked to walk on the treadmill at their preferred speed for 5 min to refamiliarize them with the experimental setting. Afterwards, they had to navigate under all three navigation support conditions in a counterbalanced order to control for daily fluctuations in performance and familiarization with the setting. Before each trial, the experimenter explained the task condition for the trial in question, and the participant was given the chance to try out this condition in the practice zoo. The experimenter did not highlight a specific navigation strategy (e.g., use the landmarks to orientate) but explained the condition (e.g., what the virtual guide means) in detail. Before both the practice and testing trials, a plan of the environment, including the landmarks, the starting point, and the goal only, were presented for 20 s. No paths were shown, and all plans were correctly oriented.

Data Processing and Statistical Analyses

Data Processing

Kinematic data from the lower limb markers were processed and analyzed separately for each trial and participant. In view of the large amount of motion data, we analyzed the motion data between the second and fifth intersection of each participant's route in each trial. In this manner, we made sure that the participants' motion data were captured in situations with comparable motor and cognitive demands. In addition, we deleted the time spent in crossings to avoid recording artifacts from virtual turns. The data were represented as Cartesian coordinates in an array of 5500 × 42 dimensions (27.5 seconds sampled at 200 Hz; 3D info for 14 markers). After correcting for movement relative to the treadmill (e.g., from temporary lagging behind the constant velocity), the data were submitted to a principal component analysis (PCA) to split them into main and residual (regular and irregular) components (Daffertshofer, Lamoth, Meijer, & Beek, 2004). This analysis was performed separately for individual trials. Our measure of gait regularity was the *residual variance* (RV), defined as the relative amount of variance in the residual pattern (expressed as percentage of total variance), with lower values indicating greater gait regularity. This procedure is described in Verrel et al. (2009). In addition, the participants' shift on the treadmill in anterior-posterior and left-right direction was determined by calculating the mean position of the lower limb markers. The variability of the participants' positional shift (VPS) in anterior-posterior (VPS-1) and right-left (VPS-2) directions was also taken as a second variable for walking regularity, again with lower values indicating greater gait regularity. In detail, lower values in VPS-1 indicate better adaptation to walking speed, and lower values in VPS-2 indicate less sway or less need to stabilize walking by making wider steps. Navigation performance was calculated by focusing on the distance covered until the goal was reached. For convenience, we normalized the values for the shortest path from the start to the goal, so that a score of 1 means the participant took the shortest path. We also applied the natural logarithm to approximate a normal distribution and reduce differences in variability within conditions, which resulted in a value of 0 for the best performance.

Statistical Analyses

Navigation and movement performance data from both trials in each condition were averaged. Navigation performance underwent a 2 (Age Group; younger/older) × 3 (Support Condition; *no support/virtual guide/overview map*) ANOVA with repeated contrasts for the age group effect. Follow-up independent-sample *t*-tests were used to trace the sources of interactions, and to assess condition effects within each age group. Pearson's correlations were computed to examine relations of the cognitive and balance tests administered in the first session to navigation performance. For within-subject effects, multivariate F values are reported. The α level was set to $p = .05$. Partial eta square was used to report effect sizes.

Walking performance (RV, for the main pattern consisting of four PCs and VPS) was analyzed in the same way as navigation performance. Likewise, relations between navigation and walking performance were examined with Pearson's correlations.

Results

Navigation Performance

An inspection of the normalized values for distance covered to reach the goal revealed that older adults in the *no-support* condition needed, on average, twice as long as younger adults to reach the goal. Means and standard error for navigation performance are depicted as a function of age group and navigation condition in Figure 4. Figure 4 also suggests age-related differences in favor of younger men in the *no-support* and *overview-map* conditions. Both groups walked with best possible performance in the *virtu-*

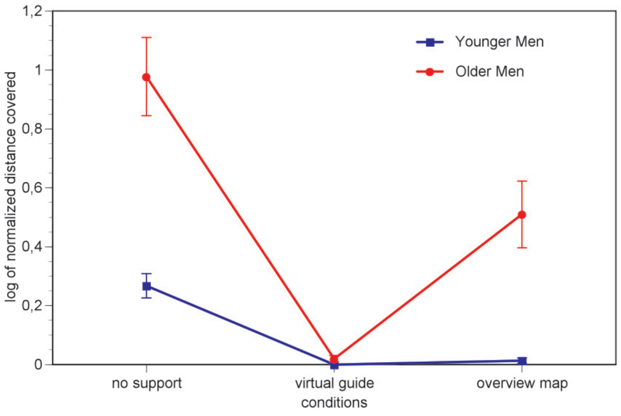

Figure 4. Logarithmic means in navigation performance. Error bars represent standard error of the logarithmic mean.

al-guide condition. The younger men were able to stay close to this level of performance in the *overview-map* condition, whereas the older men were not able to utilize the map information to the same extent. Note, however, that both groups appeared to benefit from both types of navigational support.

The Age × Support ANOVA showed main effects for Support (*virtual guide* vs. *no support*: $F(1, 34) = 77.07$, $p < .05$, $\eta^2 = .69$; *overview map* vs. *no support*: $F(1, 34) = 16.40$, $p < .05$, $\eta^2 = .33$), Age ($F(1, 34) = 46.68$, $p < .05$, $\eta^2 = .58$), and the interaction for Age × Support in *virtual-guide* vs. *no-support*, $F(1, 34) = 24.46$, $p < .05$, $\eta^2 = .42$. Follow-up *t*-tests confirmed the first observation: The main effect of age group was significant in the *no-support* condition, $t(34) = –5.12$, $p < .001$, and in the *overview-map* condition, $t(34) = –4.38$, $p < .001$, but not in the *virtual-guide* condition, $t(34) = –1.84$, $p > .08$. Pair-wise comparisons between the conditions using paired-sample *t*-tests for each age group separately showed a positive slope between the *no-support* and the other conditions: for younger men: *no support* vs. *virtual guide*, $t(17) = 6.494$, $p < .001$; *no support* vs. *overview map*, $t(17) = 6.836$, $p < .001$; for older men: *no support* vs. *virtual guide*, $t(17) = 7.182$, $p < .001$; *no support* vs. *overview map*, $t(17) = 2.683$, $p = .016$). Only the older men showed a negative slope between the *virtual-guide* and the *overview-map* condition, $t(17) = –4.297$, $p < .01$; for younger men, $p > .16$.

The correlations between both the cognitive and balance tests and navigation performance in the three conditions were not reliably different from zero among younger adults, *ps* > .16. In contrast, reliable associations between test scores and navigation performance in the *overview-map* condition were found in the older sample. Older men who navigated more efficiently in the *overview-map* condition tended to perform more accurately in the Mental Rotations test ($r = –.57$, $p = .013$) and the Digit Letter test ($r = –.63$, $p = .005$), and faster on the Timed Up and Go test ($r = .55$, $p = .019$).

Walking Variability

Scores of walking regularity based on participants' anterior-posterior and left-right shifts on the treadmill are plotted in Figure 5. In addition to mean differences between the groups for VPS in both directions (VPS-1: anterior-posterior; VPS-2: left-right), Figure 5a also suggests that condition-related differences in gait regularity were more pronounced among older men. Statistical tests confirmed this impression. Analyses based on PCA scores as dependent variable did, for the most part, not yield any reliable effects, and are not reported in detail. An Age × Support ANOVA

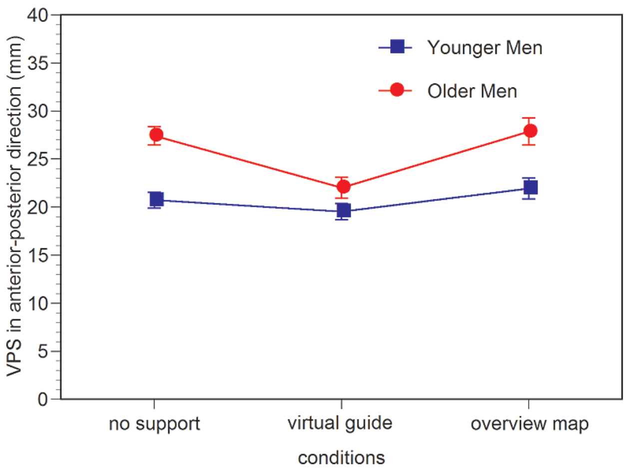

Figure 5a. Variability in participants' shift on the treadmill (VPS) in anterior-posterior direction as a function of age group and navigational conditions. Error bars represent the standard error of the mean.

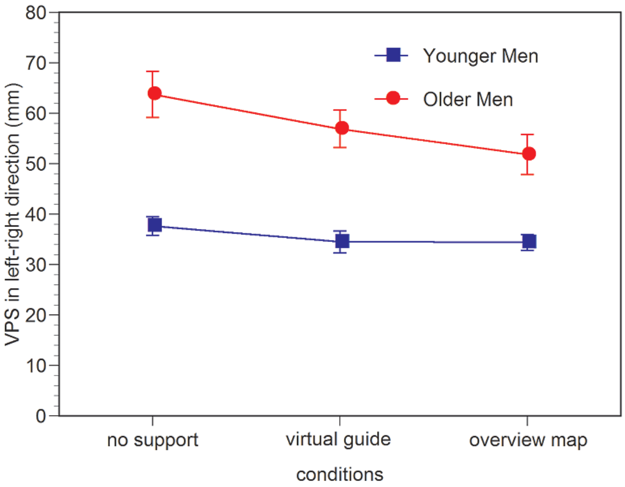

Figure 5b. Variability in participants' shift on the treadmill (VPS) in left-right direction as a function of age group and navigational conditions. Error bars represent the standard error of the mean.

showed main effects for Support (VPS-1 in *virtual guide* vs. *no support*: $F(1, 33) = 24.85$, $p < .001$, $\eta^2 = .43$; VPS-2 in *virtual guide* vs. *no support*: $F(1, 34) = 4.73$, $p < .05$, $\eta^2 = .12$; VPS-2 in *overview map* vs. *no support*: $F(1, 34) = 6.41$, $p < .05$, $\eta^2 = .16$), Age (VPS-1: $F(1, 33) = 18.88$, $p < .05$, $\eta^2 = .36$, VPS-2: $F(1, 34) = 45.00$, $p < .05$, $\eta^2 = .57$), and an Age × Support interaction for *virtual guide* vs. *no support* in VPS-1, $F(1, 33) = 10.36$, $p = .003$, $\eta^2 = .24$.

The independent-sample *t*-test revealed reliable age group differences in the *virtual-guide* condition for RV, $t(32) = –2.16$, $p = .039$, and in the *no-support*, $t(33) = –5.29$, $p < .001$, and the *overview-map* condition for VPS-1, $t(34) = –3.33$, $p = .002$, as well as in all three conditions for VPS-2, $t(34) > –4.08$, $p < .001$.

Pair-wise comparisons of the conditions using dependent-sample *t*-tests within each age group separately showed, for VPS-1 in older adults, more variability in the *no-support* than in the *virtual-guide* condition, $t(17) = 5.158$, $p < .001$, and less variability in the *virtual-guide* than in the *overview-map* condition, $t(17) = –3.757$, $p = .002$. Furthermore, for VPS-2 in older adults, we observed more variability in the *no-support* than in the *overview-map* condition, $t(17) = 2.131$, $p = .048$. All other combinations resulted in $p > .05$.

Correlations between navigation performance and walking variability did not differ reliably from zero.

Discussion

In keeping with previous research (e.g., Lövdén et al., 2005), this study revealed age-related differences in navigation both with and without navigational support. As predicted, we observed adult age differences in the effects of navigation-aid use on cognitive and sensorimotor aspects of behavior. While performance was perfect in the *virtual-guide* condition for both age groups and dramatically improved, especially for older adults, compared to the *no-support* condition, only younger adults were able to use the *overview-map* support to attain perfect performance. We interpret this pattern of findings to suggest that the *virtual-guide* support resulted in a close-to-perfect elimination of navigational load, as it simulates the behavior of following someone else, so that route planning is no longer necessary. Older adults benefit most from this type of support because navigational tasks are particularly challenging for them.

The *overview-map* support did not reduce the cognitive demands of navigation as much as the virtual-guide, presumably because the processing of this kind of support requires the investment of visuospatial attentional resources. Investing these resources did not pose any major problems to most of the younger participants but led to resource competition in most of the older adults (see also Kirasic, 2000). In line with this interpretation, correlations between marker tests of mental rotation, and perceptual speed and performance in the *overview-map* condition were restricted to older adults. The absence of similar correlations in the *no-support* condition may partly indicate that mental-rotation and speed performance was especially relevant for processing the displayed map and partly that performance among older adults was close to floor levels in the *no-support* condition.

Among older adults, walking irregularity, as indexed by participants' shift in the anterior-posterior direction, was higher in the *no-support* condition and in the *overview-map* condition than in the *virtual-guide* condition. These results are consistent with past findings showing that cognitive demands may affect sensorimotor behavior such as walking (Lövdén, Schäfer, Pohlmeyer, & Lindenberger, 2008; Verrel et al., 2009) and indicate the need to take a close look at walking stability when designing assistive navigation aids. This aid-induced decrease in shift variability may prove to be practically relevant for older adults who are at elevated risk of falling.

Conversely, the higher gait irregularity in the *overview-map* condition than in the *virtual-guide* condition indicates that cognitively demanding support may, much like unsupported navigation (Lövdén et al., 2005), divert attentional resources from maintaining a stable walking pattern, and constitute a threat for postural stability. Future studies should try to develop assistive aids that minimize the cognitive demands of navigational support for older pedestrians. In this context, it is worth noting that the evaluation of pedestrian navigation devices needs to include the assessment of gait patterns so that adverse side effects of cognitively demanding navigation aids on stability do not go unnoticed.

Against our hypotheses, older adults' gait irregularity as indexed by participants' shift in the left-right direction was lowest in the *overview-map* condition. This effect can be explained by the experimental setting, because the overview map was presented in the virtual environment and generated a "fixation point" for the participants. In addition, while using the *overview map* the participants didn't have to explore the environment as in the *no-support* condition. Subsequent experiments should take account of this issue by integrating overview maps in mobile devices or by not presenting them permanently.

Given the importance of vestibular and proprioceptive cues for developing and consolidating spatial representations (e.g., Stackman, Clark, & Taube, 2002; Waller, Loomis, & Haun, 2004), the paradigm developed for this study represents an advance over other VE paradigms. At the same time, it has some limitations. For example, the interface does not mimic normal walking perfectly because momentary variations in the speed of walking are not under the participants' control since the walking speed is fixed to a preferred speed throughout the entire trial. Moreover, actions (button presses) that change directions in the VE are clearly artificial. In addition, the body-based information is limited because shifts in orientation emanating from the optic flow of the VE are not in alignment with the actual orientation in space, which does not change. Though these limitations are compensated by the benefits of experimental control and measurement accuracy, we agree that field experiments corroborating the present findings are worth conducting.

Conclusion and Outlook: Design Guidelines for Pedestrian Navigation Aids

Assistive navigation technology shows great promise in helping older adults in the dual-task situation of walking and navigating. If such technology does justice to the reduced attentional resources and the increasing interdependence between sensorimotor and cognitive functioning, it offers the promise to improve both navigation performance and walking regularity. However, if the operation of assistive navigation technology draws too heavily on sparse cognitive resources, the benefits may be limited, up to a point where costs and adverse side effects prevail. As the results of this study illustrate, it is definitely important to consider the criterion of net resource release when designing and evaluating assistive technologies (Lindenberger et al., 2008).

Our findings also underscore the need for evaluating the effect of mobile assistive devices on behavioral domains (e.g., sensorimotor behavior) beyond the targeted behavior (e.g., navigation performance). In our view, the design of pedestrian navigation aids can profit from these findings. For example, in pedestrian situations, persons are usually walking while navigating, meaning that a support device cannot be efficient if the user has to stop while the system is providing support. Therefore, mobile navigation aids may need to provide different information layers, with different cognitive loads for walking and standing. While standing, a map may be most appropriate because of the greater amount of information it contains. In contrast, more easily accessible route information may be more appropriate during walking. Today, accelerometers are becoming a common feature of mobile devices and can be used as sensors to determine the user's gait as well as more general motion features (e.g., Bieber & Peter, 2008; Komninos, Wallace, & Barrie, 2008). Hence, we propose an extension of available resource-adaptive navigation aids, as shown in Krüger et al. (2004), that detect the user's walking states. During walking, the default option of the system would offer egocentrically oriented route information, unless the user prefers to keep to an overview map. During standing, the system would always switch to a map-like representation of the environment. By offering a variety of different formats, pedestrian assistive navigation devices can strike a balance between environmental support and self-initiated processing, and accommodate a wide range of individual differences in cognitive and sensorimotor abilities.

Acknowledgments

This work was conducted as part of the Sensorimotor-Cognitive Couplings Project at the Center for Lifespan Psychology, Max Planck Institute for Human Development, Berlin, Germany. We would like to thank our student assistants (especially Petra Bistrosch, Djamila Maleika, Nicole Malik, Katrin Sauck, and Antje Ullrich) and Gabriele Faust for their help with data collection and data preprocessing.

References

Baltes, P. B., & Baltes, M. M. (1980). Plasticity and variability in psychological aging: Methodological and theoretical issues. In G. E. Gurski (Ed.), *Determining the effects of aging on the central nervous system* (pp. 41–66). Berlin: Schering.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology and Aging, 12*, 12–21.

Bieber, G., & Peter, C. (2008). Using physical activity for user behavior analysis. In F. Makedon, L. Baillie, G. Pantziou, & I. Maglogiannis (Eds.), *Proceedings of the 1st International Conference on Pervasive Technologies Related to Assistive Environments* (Vol. 282, pp. 1–6). New York: ACM.

Charness, N., & Schaie, K. W. (2003). *Impact of technology on successful aging*. New York: Springer.

Daffertshofer, A., Lamoth, C. J. C., Meijer, O. G., & Beek, P. J. (2004). PCA in studying coordination and variability: A tutorial. *Clinical Biomechanics, 19,* 415–428.

Dixon, R. A., & Bäckman, L. (1995). Concepts of compensation: Integrated, differentiated, and Janus-faced. In R. A. Dixon & L. Bäckman (Eds.), *Compensating for psychological deficits and declines: Managing losses and promoting gains* (pp. 3–19). Mahwah, NJ: Erlbaum.

Duncan, P. W., Weiner, D. K., Chandler, J., & Studenski, S. (1990). Functional reach: A new clinical measure of balance. *Journals of Gerontology: Medical Sciences, 45,* M192–M197.

Fisk, A. D., Rogers, W. A., Charness, N., Czaja, S. J., & Sharit, J. (2004). *Designing for older adults: Principles and creative human-factors approaches*. Boca Raton, FL: CRC Press.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: Aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin, 69,* 294–305.

Jenkins, L., Myerson, J., Joerding, J. A., & Hale, S. (2000). Converging evidence that visuospatial cognition is more age-sensitive than verbal cognition. *Psychology and Aging, 15,* 157–175.

Kirasic, K. C. (2000). Age differences in adults' spatial abilities, learning environmental layout, and wayfinding behavior. *Spatial Cognition and Computation, 2,* 117–134.

Komninos, A., Wallace, R., & Barrie, P. (2008). Mobile empathy: Putting the mobile device in its user's shoes. In A. Gulz, C. Magnusson, L. Malmborg, H. Eftring, B. Jönsson, & K. Tollmar (Eds.), *Proceedings of the 5th Nordic Conference on Human-Computer Interaction: Building bridges* (Vol. 358, pp. 483–486). New York: ACM.

Krüger, A., Butz, A., Müller, C., Stahl, C., Wasinger, R., Steinberg, K.-E., & Dirschl, A. (2004). The connected user interface: Realizing a personal situated navigation service. In N. J. Nunes & C. Rich (Eds.), *Proceedings of the 9th International Conference on Intelligent User Interfaces* (pp. 161–168). New York: ACM.

Li, K. Z. H., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science, 12,* 230–237.

Light, L. L., & Zelinski, E. M. (1983). Memory for spatial information in young and old adults. *Developmental Psychology, 19,* 901–906.

Lindenberger, U. (2007). Technologie im Alter: Chancen aus Sicht der Verhaltenswissenschaften [Technology in old age: Opportunities from a behavioral-sciences perspective]. In P. Gruss (Ed.), *Die Zukunft des Alterns* (pp. 221–239). München: C. H. Beck.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging, 9,* 339–355.

Lindenberger, U., & Lövdén, M. (2006). Co-constructing human engineering technologies in old age: Lifespan psychology as a conceptual foundation. In P. B. Baltes, P. A. Reuter-Lorenz, & F. Rösler (Eds.), *Lifespan development and the brain: The perspective of biocultural co-constructivism* (pp. 350–375). New York: Cambridge University Press.

Lindenberger, U., Lövdén, M., Schellenbach, M., Li, S.-C., & Krüger, A. (2008). Psychological principles of successful aging technologies: A critical review. *Gerontology, 54,* 59–68.

Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: Increase in dual-task costs from young adulthood to old age. *Psychology and Aging, 15,* 417–436.

Lindenberger, U., Mayr, U., & Kliegl, R. (1993). Speed and intelligence in old age. *Psychology and Aging, 8,* 207–220.

Lipman, P. D. (1991). Age and exposure differences in acquisition of route information. *Psychology and Aging, 6,* 128–133.

LoPresti, E. F., Mihailidis, A., & Kirsch, N. (2004). Assistive technology for cognitive rehabilitation: State of the art. *Neuropsychological Rehabilitation, 14,* 5–39.

Lövdén, M., Ghisletta, P., & Lindenberger, U. (2004). Cognition in the Berlin Aging Study (BASE): The first 10 years. *Aging, Neuropsychology, and Cognition, 11,* 104–133.

Lövdén, M., & Lindenberger, U. (2005). Development of intellectual abilities in old age: From age gradients to individuals. In O. Wilhelm & R. W. Engle (Eds.), *Handbook of understanding and measuring intelligence* (pp. 203–221). Thousand Oaks, CA: Sage.

Lövdén, M., Schäfer, S., Pohlmeyer, A. E., & Lindenberger, U. (2008). Walking variability and working memory load in aging: A dual-process account relating cognitive control to motor control performance. *Journal of Gerontology: Psychological Sciences, 63,* P121–P128.

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. *Psychology and Aging, 20,* 683–694.

Moffat, S. D., Zonderman, A. B., & Resnick, S. M. (2001). Age differences in spatial memory in a virtual environment navigation task. *Neurobiology of Aging, 22,* 787–796.

Park, H., Collins, D. R., & Turvey, M. T. (2001). Dissociation of muscular and spatial constraints on patterns of interlimb coordination. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 32–47.

Podsiadlo, D., & Richardson, S. (1991). The Timed Up and Go: A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society, 39,* 142–148.

Riediger, M., Li, S.-C., & Lindenberger, U. (2006). Selection, optimization, and compensation (SOC) as developmental mechanisms of adaptive resource allocations: Review and preview. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (6th ed., pp. 289–313). Amsterdam: Elsevier.

Salthouse, T. A., & Mitchell, D. R. D. (1989). Structural and operational capacities in integrative spatial ability. *Psychology and Aging, 4,* 18–25.

Schäfer, S., Huxhold, O., & Lindenberger, U. (2006). Healthy mind in healthy body? A review of sensorimotor-cognitive interdependencies in old age. *European Review of Aging and Physical Activity, 3,* 45–54.

Schellenbach, M., Krüger, A., Lövdén, M., & Lindenberger, U. (2007). A laboratory evaluation framework for pedestrian navigation devices. In P. H. J. Chong & A. D. Cheok (Eds.), *Proceedings of the 4th International Conference on Mobile Technology, Applications, and Systems and the 1st International Symposium on Computer Human Interaction in Mobile Technology* (pp. 495–502). New York: ACM.

Spirduso, W. W., Francis, K., Eakin, T., & Stanford, C. (2005). Quantification of manual force control and tremor. *Journal of Motor Behavior, 37,* 197–210.

Stackman, R. W., Clark, A. S., & Taube, J. S. (2002). Hippocampal spatial representations require vestibular input. *Hippocampus, 12,* 291–303.

Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of 3-dimensional spatial visualization. *Perceptual and Motor Skills, 47,* 599–604.

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. *Psychology and Aging, 24,* 75–81.

Waller, D., Loomis, J. M., & Haun, D. B. M. (2004). Body-based senses enhance knowledge of directions in large-scale environments. *Psychonomic Bulletin and Review, 11,* 157–163.

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