Psychology and Aging
2011, Vol. 26, No. 2, 253–259

0882-7974/11/$12.00 DOI: 10.1037/a0022929

BRIEF REPORT

Increased Cognitive Load Leads to Impaired Mobility Decisions in Seniors at Risk for Falls

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Successful mobility requires appropriate decision-making. Seniors with reduced executive functioning—such as senior fallers—may be prone to poor mobility judgments, especially under dual-task conditions. We classified participants as “At-Risk” and “Not-At-Risk” for falls using a validated physiological falls-risk assessment. Dual-task performance was assessed in a virtual reality environment where participants crossed a simulated street by walking on a manual treadmill while listening to music or conversing on a phone. Those “At-Risk” experienced more collisions with oncoming cars and had longer crossing times in the Phone condition compared to controls. We conclude that poor mobility judgments during a dual-task leads to unsafe mobility for those at-risk for falls.

Keywords: aging, cognitive load, falls risk, dual-task

Cognition is an important contributor to safe mobility through the environment. Although physical abilities (e.g., balance) undoubtedly factor into our capacity to be mobile, specific cognitive processes such as attention, planning, and decision-making collectively ensure our safety during mobility.

Within the multiple domains of cognition, executive functions—or higher order cognitive processes—are integral to safe mobility (Anstey, von Sanden, & Luszcz, 2006; Persad et al., 1995). These include the ability to concentrate, attend selectively, and to plan and strategize. Selective attention to hazards in our environment is essential for safe mobility. Our ability to effectively plan and strategize contributes to decision-making about when and where to move. Importantly, a failure to make appropriate and timely decisions may result in unsafe mobility, such as falls.

With age, walking requires greater cognitive effort and a larger allocation of attentional resources (Lindenberger, Marsiske, & Baltes, 2000; Lovden, Schaefer, Pohlmeyer, & Lindenberger, 2008; Wollacott & Shumway-Cook, 2002; Yogev-Seligmann, Hausdorff, & Giladi, 2008). This likely results from reduced parietal cortex function, leading to a higher need for sensorimotor processing (Huxhold, Li, Schmiedek, & Lindenberger, 2006). Additionally, impaired prefrontal cortex function results in reduced employment of attentional resources for effective postural control (Huxhold et al., 2006).

Hence, not surprisingly, reduced executive functioning is a risk factor for falls (Tinetti, Speechley, & Ginter, 1988). Falls, a clinical consequence of unsafe mobility and a significant health care problem, occur in approximately 30% of community-dwelling seniors (Skelton & Todd, 2004; Tinetti et al., 1988). Falls are often attributed to impaired physical abilities but recent evidence highlights the role of reduced executive functioning. Anstey and col-

This article was published Online First April 4, 2011.

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This work was supported by The National Institute on Aging (R37 AG025667, R01 AG25032) to Arthur F. Kramer and the Canadian Institute of Health Research (MOB-93373) to Teresa Y. L. Liu-Ambrose. The authors would like to thank Feng Zhao and Shanna Wilcox for their assistance with participant recruitment and data collection. Lindsay S. Nagamatsu is a trainee with the Michael Smith Foundation for Health Research (MSFHR) and the Natural Sciences and Engineering Research Council of Canada (NSERC). Todd C. Handy and Teresa Y. L. Liu-Ambrose are both MSFHR Scholars.

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leagues (Anstey et al., 2006) found that cognitive performance on "Similarities," a test of verbal reasoning, was inversely associated with falls rate. Also, performance on the Stroop Color-Word Test, a test of conflict resolution, predicts falls status beyond that explained by age and functional motor ability (Rapport, Hanks, Millis, & Deshpande, 1998). Both verbal reasoning and conflict resolution are dimensions of executive functioning (Lezak, 1995; Stuss & Alexander, 2000).

To better understand the interaction between executive functioning and falls risk, studies have relied on dual-task paradigms incorporating a motor task with a concurrent cognitive task. These studies consistently demonstrate that reduced gait speed during dual-task performance is associated with falls risk (Verghese et al., 2002) and that impairments in the ability to hold a conversation while walking are notable in senior fallers (Lundin-Olsson, Nyberg, & Gustafson, 1997). However, studies to date have not examined the role of decision-making relevant to navigation and mobility during dual-task performance.

Previous studies are also limited by their use of laboratory-based dual-task paradigms. While dual-task paradigms such as reciting the alphabet or counting backwards while walking result in changes in overt motor outcomes (Verghese et al., 2002), they are not activities performed in the real world. Rather, in our modern and increasingly technology-based world, we are more likely to engage in conversations on a cell phone or listen to an iPod as we walk down the street.

To address these limitations, we examined the relationship between decision-making and falls risk in the context of a simulated real-world task using an immersive virtual reality environment (VRE). We compared seniors at-risk for falls with seniors not-at-risk on the ability to successfully cross a busy street under a single-task and two different dual-task conditions. The primary objective was to determine if there were differences between the two groups in their ability to judge when it was safe to cross the street under dual-task conditions. The secondary objective was to determine if there were differences in gait speed between the two groups under single and dual-task conditions. Additionally, we included a computer-based dual-task to assess cognitive aspects of performing a dual-task independent of mobility.

Method

Participants

Thirty-three community-dwelling seniors participated (16 female; Mean age = 73.12 years, *SD* = 4.46). Participants were recruited via advertisements and participant pools from previous studies within the lab at the University of Illinois. All interested participants were initially screened by phone. Inclusion criteria were: (a) community-dwelling; (b) age 65 years or older; (c) normal or corrected to normal vision, with visual acuity of 20/40 or better based on Snellen chart performance; (d) no diagnosis of a neurological or neuropsychological disorder; (e) not currently taking medication impeding balance; and (f) able to walk ≥ 0.5 kilometers unaided.

Procedure

There were two experimental sessions, each 1.5 hours. In Session 1, participants completed descriptive measurements, a computer dual-task paradigm, and falls risk assessment. In Session 2, participants performed the primary experimental task (VRE). Session order was counterbalanced between subjects. All participants provided written informed consent.

Measures

Descriptive measures. We measured age in years, standing height in centimeters, and mass in kilograms. We assessed global cognition using the Montreal Cognitive Assessment (MOCA), where scores ≥ 26 indicate normal cognitive performance. Current level of physical activity was determined by the Physical Activities Scale for the Elderly (PASE) (Washburn, Smith, Jette, & Janney, 1993), in which physical activities completed in the past 7-day period are reported. General mobility and balance were measured by the Timed Up and Go Test (TUG) (Podsiadlo & Richardson, 1991) and the Short Performance Physical Battery (SPPB).

Falls risk. Physiological falls risk was assessed by the short form of the Physiological Profile Assessment (PPA) (Lord, Menz, & Tiedemann, 2003). The PPA is a valid and reliable measure of falls risk in seniors, with 75% predictive accuracy for falls in older adults. Based on performance of five physiological domains (reaction time, contrast sensitivity, sway, proprioception, and knee extension strength), the PPA computes a falls risk score for each individual. We classified our participants as "At-Risk" or "Not-At-Risk" for future falls according to their PPA scores. Based on previous work demonstrating that a PPA cutoff score of 0.6 validly classifies seniors into separate falls risk categories, we decided a priori to divide our participants into two groups using this cutoff score (i.e., <0.6 = "Not-At Risk"; ≥0.6 = "At-Risk") (Delbaere et al., 2010). While the TUG is another measure used to determine falls risk, we chose to divide our group based on PPA because it is currently the most valid way to assess falls risk (Lord et al., 2003).

Computer dual-task performance. Cognitive dual-task ability was assessed using a computer-based paradigm. Participants viewed a computer display with either a single number or letter (single task) or a number and letter concurrently (dual task). Participants were required to respond by pressing a button with their left hand for letters and right hand for numbers (index fingers corresponding to "B" and "2" and middle fingers corresponding to "A" and "3," respectively). Reaction times and accuracy were recorded.

CAVE virtual environment. Dual-task ability in simulated "real-life" was assessed using the CAVE Automatic Virtual Environment (CAVE; Beckman Institute, Urbana-Champaign, Illinois; http://isl.beckman.illinois.edu/Labs/CAVE/CAVE.html). The CAVE consists of four viewing screens (one in the front, one on each side, and a floor), each measuring 303 cm wide × 273 cm high and a screen resolution of 1024 × 768 pixels. Participants stood approximately 149 cm away from the front screen, creating a viewing angle of 91° × 85°. A custom designed program (Illinois Simulation Laboratory) provided the environment presentation, motion simulation, and data acquisition. Images were projected from a PC running on a 64-bit Windows Server (2003) and graphics were presented by an nVidia Quadro Plex 1000 Model 2. We monitored head movements (i.e., the number of times participants looked in either direction in preparation and while crossing the street) through an Ascension Flock of Birds 6DOF electromagnetic tracker, where head movements were defined as moving 10° in one direction to at least 10° in the opposite direction. Depth perception was created by wireless CrystalEyes liquid crystal shutter goggles, rapidly alternating the display to each eye, thus providing the "virtual reality experience."

Participants viewed a VRE simulating a two-way busy street, with cars approaching from both directions (Figure 1). Starting at a crosswalk, they had to cross two lanes of traffic, totaling eight meters in width. To cross the street, participants walked on a LifeGear Walkease manual treadmill, which was synced to the VRE. Cars moved at a constant speed of 54 km/hr, with consistent spacing of either 75 or 90 meters apart for each trial.

Participants were instructed to cross the street without getting hit by oncoming traffic. They were permitted to walk forward only and could walk as fast as necessary without running. Trials began after passing through a gate, after which they had 90 s to complete the trial. There were eight practice trials. The actual experiment comprised 60 trials. Participants were permitted to take breaks between trials.

The experiment was a blocked design, with three experimental conditions: (a) No Distraction; (b) Music; and (c) Phone. Each block consisted of 10 trials, and each of the three conditions was completed twice (i.e., 20 total trials per condition). Condition order was randomized. In the No Distraction condition (i.e., control condition), participants crossed the street without a secondary task. In the Music condition, participants listened to one of several pre-made playlists through earphones on an iPod while attempting to cross the street. In the Phone condition, participants crossed the street while conversing on the phone with a confederate via a hands-free headset. Experimenters had a set list of questions to engage the participants. An experimenter was present in the room to supervise the participant at all times.

Analysis

Data was imported into SPSS (Version 16.0 for MAC). Descriptive measures and computer-based dual-task performance were analyzed using independent-samples *t*-tests to test for between-group differences. Primary CAVE measures were analyzed using repeated-measures ANOVAs, with condition as the within-subject factor, and group as the between-subject factor. We analyzed: (a) the number of successful trials completed, defined as crossing the street without being hit; (b) whether unsuccessful trials were the result of collisions versus running out of time; (c) number of collisions occurring in the first lane of traffic (assuming collisions in the first lane indicate reduced decision-making ability, or judgment, regarding when to initiate street-crossing); and (d) using only successful trials, length of time to cross the street. Body mass index (BMI; kg/m^2) was included as a covariate for the analysis of length of time to cross the street, because stride length is an important contributor to gait speed (Callisaya, Blizzard, Schmidt, McGinley, & Srikanth, 2010; Kuo, Lin, Yu, Wu, & Kuo, 2009). For all analyses, the overall alpha level was set at $p < .05$.

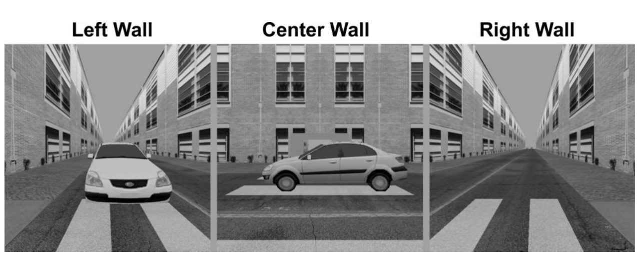

Figure 1. A screen-shot of the virtual reality display. Note that the image was created from still captures of three separate images projected on the three walls of the CAVE (left, straight ahead, and right). In the virtual environment, the road appears as one straight line, perpendicular to the participant. Reprinted from "Pedestrians, vehicles, and cell phones," by M. B. Neider, J. S. McCarley, J. A. Crowell, H. Kaczmarski, and A. F. Kramer, 2010, *Accident Analysis and Prevention, 42*, pp. 589–594. Copyright 2010 by Elsevier. Reprinted with permission.

Results

Descriptive Measures

Table 1 provides results of the descriptive measures. Of these measures, both the TUG score and PPA score significantly differed between the groups, $t(31) = 2.53$, $p = .02$ and $t(31) = 7.52$, $p < .001$, respectively.

Computer Dual-Task Performance

"At-Risk" seniors performed significantly worse in the dual-task compared to those "Not-At-Risk" (Table 2). Specifically, "At-Risk" individuals had both reduced accuracy, $F(1, 32) = 5.64$, $p = .02$, $\eta_p^2 = 0.15$ and slower reaction times, $F(1, 32) = 4.65$, $p = .04$, $\eta_p^2 = 0.13$ in the dual-task condition, relative to their "Not-At-Risk" peers. In the single-task condition, there were no significant between-groups differences for either accuracy or reaction times ($p = .11$ and 0.93, respectively). Additionally, the number of successful crossing trials in the CAVE Phone condition was positively correlated with dual-task accuracy performance on the computer task, $r = .48$, $p = .004$. Furthermore, time to cross the street in the CAVE Phone condition was positively correlated with dual-task reaction time in the computer task, $r = .54$, $p = .001$.

CAVE

Trial success. Regarding the number of times participants successfully crossed the street, there was a significant main effect of condition, $F(2, 62) = 6.65$, $p = .002$, $\eta_p^2 = 0.18$. Specifically, follow-up simple contrasts revealed that participants performed worse in the Phone condition compared to No Distraction, $F(1, 31) = 11.93$, $p = .002$, $\eta_p^2 = 0.28$. "At-Risk" participants performed significantly worse overall than those "Not-At-Risk", as confirmed via a significant main effect of group, $F(1, 31) = 4.34$, $p = .05$, $\eta_p^2 = 0.12$. Additionally, there was a significant condition × group interaction, $F(2, 62) = 3.69$, $p = .01$, $\eta_p^2 = 0.11$. Follow-up analyses revealed that "At-Risk" participants successfully crossed the street significantly fewer times in the Phone condition relative to those "Not-At-Risk", $F(1, 32) = 7.86$, $p = .009$, $\eta_p^2 = 0.20$, but no significant between-groups differences were found for the No Distraction ($p = .17$) and Music ($p = .25$) conditions (Figure 2a).

Table 1
Descriptive Measures

Measure	"Not-At-Risk" (n = 17)	"At-Risk" (n = 16)	Effect sizes[a], η_p^2
Age, years	71.9 (4.1)	74.4 (4.6)	0.09
Body mass index, kg/m^2	27.1 (4.2)	25.9 (3.2)	0.03
Education, No. (%)			
No high school diploma	0 (0)	0 (0)	
High school diploma	3 (17.6)	2 (12.5)	
Some university certificate or diploma	6 (35.3)	3 (18.8)	
University degree	2 (11.8)	4 (25.0)	
Post-graduate	6 (35.3)	7 (43.8)	
Gender, No. (%)			
Female	8 (47.1)	8 (50.0)	
Comorbidities, No.	1.53 (1.70)	1.75 (1.24)	0.01
PASE score	182.3 (82.0)	138.7 (61.3)	0.09
MOCA score[b]	24.9 (2.8)	24.1 (2.2)	0.03
Physical battery[c]	9.6 (1.4)	8.5 (1.7)	0.11
Physiological Profile Assessment score	−0.2 (0.5)	1.2 (0.6)	0.65**
Timed Up and Go score, s[d]	9.8 (1.7)	11.4 (2.0)	0.17*

Note. Unless otherwise indicated, data are expressed as mean (*SD*). Percentages have been rounded and may not total 100. PASE = Physical Activity Scale for the Elderly; MOCA = Montreal Cognitive Assessment.
[a] Effect sizes calculated using η_p^2. [b] Maximum is 30 points. [c] Maximum is 12 points. [d] Time recorded in seconds.
* $p < .05$. ** $p < .001$.

For unsuccessful trials, we examined rates of collisions versus time-outs (Table 2). Collisions were defined as trials where participants were struck by an oncoming car during crossing. Time-outs were defined as trials where participants were unable to cross the street within the allotted 90-s time, and were not struck. For collisions, there was a significant main effect of condition, $F(2, 62) = 3.26$, $p = .05$, $\eta_p^2 = 0.10$. Follow-up simple contrasts reveal that overall, participants experienced more collisions in the Phone condition relative to No Distraction, $F(1, 31) = 7.24$, $p = .11$, $\eta_p^2 = 0.19$. There was also a significant main effect of group, $F(1, 31) = 4.57$, $p = .41$, $\eta_p^2 = 0.13$, where "At-Risk" participants experienced more collisions than those "Not-At-Risk." Lastly, there was a marginally significant condition × group interaction, $F(2, 62) = 12.64$, $p = .06$, $\eta_p^2 = 0.09$. Follow-up analyses show that "At-Risk" participants experienced more collisions in the Phone condition, relative to age-matched controls, $F(1, 32) = 8.39$, $p = .007$, $\eta_p^2 = 0.21$. There were no significant between-groups differences for the No Distraction ($p = .18$) and Music ($p = .25$) conditions. For time-outs, there was a significant main effect of condition, $F(2, 62) = 4.58$, $p = .01$, $\eta_p^2 = 0.13$, with more time-outs observed for the Phone condition relative to No Distraction, $F(1, 31) = 4.89$, $p = .04$, $\eta_p^2 = 0.14$. There were no

Table 2
Task Performance in the CAVE and on the Computer-Based Dual-Task as a Function of Condition

	CAVE[a]			
	"Not-At-Risk"		"At-Risk"	
	Collision rate	Time out rate	Collision rate	Time out rate
No Distraction	20.88 (12.78)	0.59 (2.43)	29.06 (20.43)	0.94 (3.75)
Music	23.82 (13.29)	0.29 (1.21)	30.31 (18.12)	0.63 (2.50)
Phone	22.35 (15.12)	2.35 (6.15)	40.31 (20.29)	3.75 (11.18)
	Computer-based dual-task[b]			
	"Not-At-Risk"		"At-Risk"	
	Reaction time	Accuracy	Reaction time	Accuracy
Single task	1099.81 (103.24)	85.60 (13.28)	1107.39 (313.77)	76.10 (19.75)
Dual task	1505.04 (121.97)	57.95 (19.95)	1585.66 (89.09)	40.33 (22.68)

[a] Data presented as mean percentage rates (*SD*). Rates calculated as number of unsuccessful trials divided by total number of trials × 100. [b] Data presented as mean reaction time (s) and accuracy (% correct responses) (*SD*).

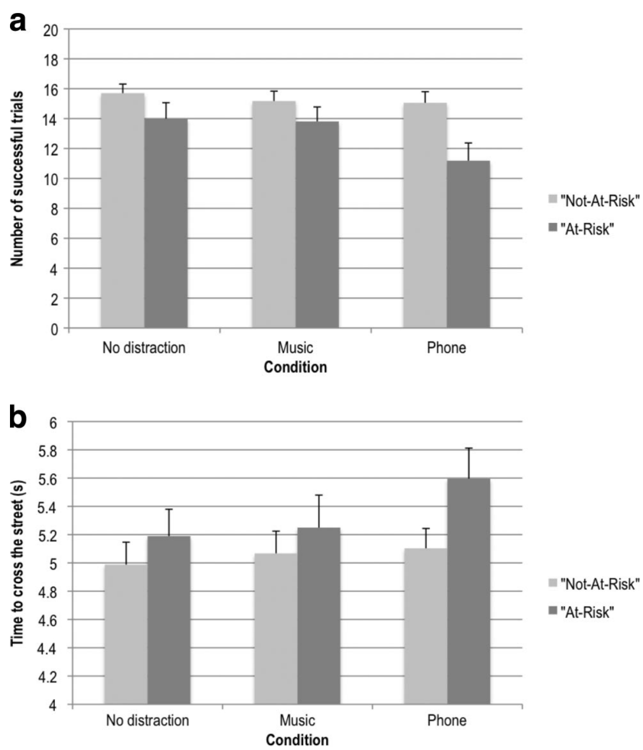

Figure 2. Street crossing performance as a function of condition (No distraction, Music, and Phone) and falls-risk group. Error bars represent standard errors of the mean. (a) Mean number of trials successfully completed. Those "At-Risk" for falls successfully crossed the street significantly fewer times than those "Not-At-Risk" in the Phone condition. (b) Mean length of time taken to cross the street on successful trials. Those "At-Risk" for falls crossed the street significantly slower than those "Not-At-Risk" in the Phone condition.

significant between-group differences, $p > .05$ for number of time-outs.

Street-crossing time. For the length of time taken to cross the street, there was a significant main effect of group, $F(1, 30) = 4.68$, $p = .04$, $\eta_p^2 = 0.14$, indicating that overall, those "At-Risk" for falls were significantly slower to cross the street. More specifically, however, "At-Risk" participants crossed the street significantly slower in the Phone condition compared to those "Not-At-Risk" (Figure 2b), as indicated by the significant condition × group interaction, $F(2, 60) = 3.45$, $p = .04$, $\eta_p^2 = 0.10$. Follow-up analyses revealed significant between-group differences in the Phone condition, $F(1, 32) = 9.00$, $p = .005$, $\eta_p^2 = 0.23$. There were no significant between-groups differences for the No Distraction ($p = .12$) and Music ($p = .14$) conditions.

Discussion

To examine the relationship between mobility judgments and falls-risk in the real-world, participants "At-Risk" for falls and those "Not-At-Risk" crossed a busy street in a VRE while completing a secondary task. We report two key results. First, seniors "At-Risk" were less successful at street-crossing while conversing on a phone. Reduced success rate was secondary to greater number of collisions in the first lane of traffic. Second, those "At-Risk" crossed the street significantly slower compared with those "Not-At-Risk" in the Phone condition. Given these results, several points of discussion follow.

First, our results are consistent with previous findings that dual-task performance leads to reduced gait speed in senior fallers (Faulkner et al., 2007; Lundin-Olsson, Nyberg, & Gustafson, 1998; Verghese et al., 2002; Yogev-Seligmann et al., 2008). In tasks that require performance of a physical task (e.g., walking) and a concurrent cognitive task (e.g., talking), young adults tend to prioritize gait and compromise cognitive performance (Bloem, Valkenburg, Slabbekoorn, & Willemsen, 2001; Yogev-Seligmann et al., 2008). However, Parkinson's patients and senior fallers are susceptible to increased gait variability and reduced ability to prioritize gait performance under dual-task conditions (Beauchet et al., 2007; Bloem, Valkenburg, Slabbekoorn, & van Dijk, 2001; Chapman & Hollands, 2007; Yogev-Seligmann et al., 2008). It has therefore been suggested that reduced executive functioning leads to impaired divided attention and ineffective use of available resources, resulting in reduced gait speed (Yogev-Seligmann et al., 2008).

More notably, our study is the first to show that individuals "At-Risk" for falls may have reduced ability to plan and decide on their mobility through the physical environment when cognitively loaded. Reduced abilities to plan and judge under dual-task conditions among seniors "At-Risk" for falls are likely to be secondary to reductions in cognitive capacity evident in this population (Rapport et al., 1998; Springer et al., 2006). Reduced judgment resulting from increased cognitive load may result in two forms of behavior: (a) conservative behavior, or (b) risky behavior. A previous study used the same VRE paradigm to examine the effects of dual-task performance on pedestrian behavior among college-aged adults (Neider, McCarley, Crowell, Kaczmarski, & Kramer, 2010). While talking on a cell phone, young adults were more cautious crossing the street, such that participants took longer to both initiate and complete street-crossing. Young adults also timed-out more during the phone condition. Hence, dual-task demands resulted in more cautious behavior among young adults. In contrast, seniors "At-Risk" for falls engaged in risk-taking behavior, jeopardizing their safety. Specifically, they had significantly more collisions in the first lane than those "Not-At-Risk," suggesting that seniors at risk for falls were less able to appropriately judge when to initiate street crossing. Interestingly, in a previous study senior fallers cited their own risk-taking behaviors as the most common cause of falling, rather than their health or environmental factors (Hornbrook, Wingfield, Stevens, Hollis, & Greenlick, 1991). Hence, an inability to judge one's own neuromuscular constraints to plan successful movements, as limited by executive functioning impairments, may be linked to falls-risk (Liu-Ambrose, Ahamed, Graf, Feldman, & Robinovitch, 2008).

Our results also suggest that dual-task demands per se may not be detrimental to safe mobility. Rather, the nature of the concurrent task demands (i.e., a "passive" task, such as listening to music versus an "active" task, such as talking on the phone) is important. This factor may have contributed to the equivocal results to date on the association between dual-task performance and falls risk. For example, Verghese and colleagues (Verghese et al., 2002) found that reciting the alphabet while walking significantly reduced gait speed in fallers. In contrast, Bootsma-van der Wiel et al. (Bootsma-van der Wiel, et al., 2003) asked participants to count backwards while walking, and found that dual-task performance is not a significant predictor of falls. Hence, future studies are needed to better ascertain the modulating effect of cognitive load on the relationship between dual-tasking ability and falls risk.

Finally, while there are certainly differences in mobility between those "At-Risk" and those "Not-At-Risk" for falls, our results were not merely due to physical differences between the two groups. First, there were no group differences in the Short Performance Physical Battery and current physical activity level. Second, gait speed was not significantly different between the two groups in both the Music and No Distraction conditions. Third, results from the computer-based dual-task support the notion that our results are likely due to between-groups differences in cognitive control, as results from the computer task and the CAVE data positively correlate. Together, our findings suggest that differences between our falls-risk groups can be attributed, at least in part, to cognitive abilities.

We recognize the limitations of our study. First, due to recruitment issues, we were unable to directly assess seniors with a history of falls (i.e., "fallers") versus seniors without a history of falls (i.e., "non-fallers"). Instead, our groups were defined using a validated PPA cutoff score to identify those "At-Risk" versus those "Not-At-Risk" for future falls (Lord et al., 2003). Second, our ability to make conclusions regarding the Music condition is limited by our lack of behavioral measures of the secondary task. Specifically, it is possible that participants were simply "tuning-out" the music, performing only the walking task without a secondary cognitive task. However, listening does not appear to impair secondary task performance (McCarley et al., 2004). Therefore, our results are more likely due to actual differences between listening and talking, rather than mere task engagement. Another limitation was that we did not compensate for the fact that our viewing distance requires a small accommodative response in order to yield a well-focused retinal image. This may be addressed in future studies by adjusting the LCD stereo goggles. A fourth limitation is that our virtual environment did not replicate any traffic sounds. Future studies may examine how inclusion of road noise may affect street-crossing performance by providing auditory cues. Lastly, our task was designed to be more difficult than crossing the street in real life. Indeed, street-crossing performance in all conditions was markedly lower than what we would expect in real life. However, this was necessary in order to ensure that there would be performance variability between participants. While we recognize that this is certainly a limitation of our current study, we highlight that our study has increased ecological validity, compared to strictly laboratory-based tasks, and that our results here represent the trade-off between internal and external validity.

To conclude, our study suggests that critical mobility decisions, such as when to cross a busy street, may be impaired in those even at moderate risk for falls (i.e., mean PPA score of 1.2). These impaired judgments result from increased cognitive load. We highlight the value of increasingly ecologically valid paradigms designed to test "real-life" situations. Given the complex relationship between cognitive and physical abilities, it is important to understand how they may interact in the context of the real world.

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Received June 28, 2010
Revision received November 30, 2010
Accepted December 6, 2010 ■