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Dual-Tasking Impacts Gait, Cognitive Performance, and Gaze Behavior During Walking in a Real-world Environment in Older Adult Fallers and Non-fallers

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Abstract

Introduction: Everyday walking often involves simultaneous performance of a cognitive task in environments with competing auditory and visual stimuli. Previous research has not evaluated task performance in these situations, where older adults are known to fall, limiting our understanding of how older adults adjust their gait, visual scanning (gaze), and cognitive processing to avoid falls (or not). The purpose of this study was to examine the effect of dual-task walking in a high-distraction real-world environment on cognitive performance, gait performance, and gaze behavior in older adult fallers relative to non-fallers.

Methods: Fourteen community-dwelling, older adult fallers (76.6±9.1 years, 11 females) and 15 community dwelling, older adult non-fallers (77.4±7.6 years, 11 females) participated. Participants performed single-task walking, single-task cognitive (seated category naming), and dual-task

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walking (category naming + walking) trials for 1 minute each in a real-world environment (busy hospital lobby). Gait speed, stride length variability, stride duration variability, gaze fixation duration on 6 areas of interest (AOIs), and percentage of time fixating on 6 AOIs were recorded during single- and dual-task walking trials. Number of correct responses, time to first response, and mean subsequent response time (measure of rate of decline of response retrieval throughout trial) were determined for single-task cognitive and dual-task walking trials. Two-way MANCOVAs and MANOVAs were used to compare the effects of fall status and task condition on gait and cognitive variables. Hierarchical linear regression models were used to assess predictors of gaze behavior variables.

Results: Compared to single-task, during dual task trials, participants walked 0.21 m/s slower, had 1.5 fewer verbal responses, and a 2823 ms shorter mean subsequent response time, indicating a faster declining rate of retrieval during the cognitive task. Additionally, during dual-task walking, participants fixated their gaze on Far People (AOI) for a significantly smaller percentage of time and on the Near Walking Path (AOI) for a significantly greater percentage of time than during single-task walking. During all trials, being a non-faller predicted a longer average fixation duration on the Far Environment (AOI) than for fallers. Environmental busyness, baseline gait speed, and baseline executive function impacted gaze behavior.

Conclusion: All participants exhibited dual-task decrements in gait and cognitive performance and changes in gaze behavior from single- to dual-task walking. Perhaps of more importance, non-fallers appear to have had more freedom to divert their gaze to less relevant environmental stimuli while walking, and two measures of fall risk impacted patterns of gaze behavior differently. Thus, overt visual attention during walking in real-world environments should be further explored in relation to fall risk.

Keywords

Aged; Accidental falls; Dual-task gait; Visual attention; Cognition

1. Introduction

Falling is a major issue in the older adult population because it can result in physical injuries, anxiety and a consequent reduction in activity levels, declines in functional capability, and early mortality [1-4]. Older adults who fall commonly report falling while distracted or while trying to perform two tasks at once [3,5,6]. However, these everyday circumstances are not commonly assessed in typical testing of fall risk factors. Therefore, a better understanding of how distractions and performing two tasks at once (i.e., dual tasking) is related to fall status is warranted. Specifically, understanding how dual-task performance in a distracting environment differs between older adult fallers and non-fallers may provide new information about potential fall risk factors that could be used to develop more effective fall prevention programs for community-ambulating older adults.

Dual-task walking is critical to carrying out activities of daily living. Indeed, everyday walking often involves simultaneous performance of a cognitive task, such as walking while talking with a companion or planning to navigate around moving people/obstacles. The successful performance of these dual tasks involves the ability to adjust gait, timely cognitive processing, and focused/varied visual scanning, as appropriate. Dual tasking is likely a common circumstance of falls because of the frequency with which it is performed and age-related declines in sensorimotor coordination and executive function. These age-related declines can affect the ability to adjust gait while walking and can result in slowed cognitive processing speed. Furthermore, difficulty with selective attention and declines in spatial working memory can impact visuomotor adaptation, which could contribute to dual-tasking difficulties [7-10].

Previous research provides evidence of age-related declines in both cognitive and gait performance decrements while dual-task walking [11,12]. Further, older adults have been shown to prioritize the cognitive task at the expense of the gait task, and make more missteps when walking task complexity is increased [11]. Indeed, dual-task walking tends to replicate walking characteristics typical of a person's usual, community walking, more than single-task walking [12]. In terms of dual-task and faller-related changes in visual attention during walking, research has shown that older adult fallers transfer their gaze away from an obstacle in their walking path earlier than older adult non-fallers during dual- relative to single-task obstacle crossing [13]. Thus, older adult fallers seem to exhibit maladaptive changes in gaze behavior during dual-task performance [13], which have been attributed to the added cognitive load disrupting the attentional resources necessary for acquiring and processing visual information during a visually-demanding walking task [14]. Because fallers exhibit greater declines in the ability to adjust gait, cognitive processing, and visual attention than non-fallers [15-22], dual-task related changes in performance may be greater for fallers than non-fallers.

Dual-task performance recreates some of the competing demands of real-world walking, but distractions and the saliency of real-world risks may also be important. Distractions can be auditory (e.g., traffic noise and other people's conversations) or visual (e.g., people moving around us or animated billboards that grab our attention) and require individuals to focus on relevant and important environmental information while inhibiting irrelevant and distracting environmental noise to safely navigate an environment. Older adults have been shown to exhibit age-related declines in inhibition of attention, which may exacerbate difficulties with dual task walking in a relatively high-distraction real-world setting [23]. Additionally, our everyday environment includes an element of unpredictability (e.g., a dog darting into the walking path) and potential hazards (e.g., possible collisions with people and tripping over debris on the ground) that carry more serious consequences, like falling, if they are not avoided. These real-world risks and consequences likely result in changes in behavior that would not necessarily be seen in a lab environment. Indeed, a study involving young adults observed that as an outdoor walking path became increasingly rougher and more uncertain, individuals adapted their gaze behavior to accommodate more time needed to plan their walking path and exhibited more meandering walking paths to ensure safe foot placement [24]. These results differed from similar testing they did with young adults in a lab setting [25]. Further, our related research comparing gait and gaze behavior in a lab versus a real-world environment determined that the environment affects what older adults choose to visually attend to, and that there are additional gait and gaze behavior differences between fallers and non-fallers [26]. Thus, observing older adults walking in a real-world environment with additional cognitive demands as an examination of real-world fall risk factors is warranted.

While previous research has examined dual-task walking in older adults, only a few studies have explored aspects of walking in a real-world setting, and, to our knowledge, there has been no research that has evaluated performance of these complex, everyday situations comparing older adult fallers and non-fallers. Therefore, the purpose of this project was to examine how dual-tasking affects gait, visual scanning (gaze), and cognitive performance in older adult fallers and non-fallers in a real-world environment. We hypothesized that we would observe 1) dual-task effects on gait, cognition, and gaze behavior, such that older adults would exhibit slower gait speeds, greater gait variability, fewer cognitive responses, faster decline in response retrieval rate, longer fixation durations, and more frequent fixations on the travel path (i.e., narrower scan field and reduced situational awareness) compared to single-task walking; and 2) an interaction between fall status and task condition, such that the dual-task effects on gait, cognition, and gaze behavior would be greater in fallers than non-fallers.

2. Methods

2.1. Participants

Participants were older adults (at least 60 years of age) recruited from the local community. Fallers were defined as individuals who reported two or more falls in the previous twelve months. A fall was operationally defined as “an unexpected event in which the participants come to rest on the ground, floor, or lower level” [27]. To enable matching, fallers were recruited first. Non-fallers were defined as individuals who reported no falls in the previous twelve months. Non-fallers were matched to fallers on age (± 5 years), gender, and years of formal education (± 2 years). Matching on age and gender was necessary because increasing age and being female are associated with a greater risk of falling [28]. Years of education was additionally controlled for because more education has been shown to correspond with improved cognitive functioning later in life [29], which is associated with a lower risk of falling [30]. Additional inclusion criteria were ability to walk continuously for 3 minutes with or without an assistive device, verbally communicate in English, follow a 3-step command, have no orthopedic problem or pain affecting gait, no significant hearing or vision impairments, or pre-existing neurological disorders. The study was approved by the Institutional Review Board, and all participants provided informed consent before the commencement of testing. This study is part of a larger study that additionally explored the effect of environment on gait and gaze behavior in older adults [26].

2.2. Procedures

Participants completed two separate testing sessions that were separated by no more than one week. During the first testing session, participants completed a battery of assessments to evaluate their cognition, functional mobility, vision, self-reported physical activity, and self-reported balance self-efficacy. The Montreal Cognitive Assessment [31], WAIS Vocabulary subtest [32], WAIS Digit Symbol Substitution and Copy subtests [32], Comprehensive Trail Making Test (CTMT) [33], and a computerized Stroop color-word interference test were used to assess global cognition, verbal abilities, information processing speed, focused attention/inhibition of distraction, and selective attention/inhibition of habitual response, respectively. The 10 Meter Walk Test, Timed Up and Go test (TUG) [34], Four Square Step Test [35], and Dynamic Gait Index [36] were used to assess self-selected gait speed, functional mobility, dynamic balance, and dynamic balance during walking tasks, respectively. Visual acuity and contrast sensitivity were assessed using the Snellen test and the Melbourne Edge Test [37], respectively. Finally, self-reported physical activity and balance self-efficacy were assessed with the Physical Activity Scale for the Elderly [38] and the Activities-specific Balance Confidence Scale [39]. All of the included assessments have also been demonstrated to relate to fall risk. Demographic information were also collected.

During the second testing session, participants performed a series of tasks in a real-world environment (busy hospital lobby): two trials of self-selected walking (single-task gait), two trials of a seated cognitive task (single-task cognitive), and two trials of walking while performing the same cognitive task (dual-task walking), for a total of six trials. The order of trials was as follows: single-task gait, single-task cognitive, dual-task trial (2 consecutive trials), single-task cognitive, and single-task gait. This testing order and the collection of two trials for each trial condition ensured that effects of fatigue were mitigated.

Each trial was one minute in duration and all trials were conducted in the hospital lobby. The testing environment has been described in more detail elsewhere [26]. During each walking trial, participants were instructed to walk at their normal, comfortable speed along a 30 m length of the hospital lobby, turning at each end. Stride data were recorded for the entirety of each 1-minute walking trial using the 5-sensor LEGSys+ wireless system (100 Hz, Biosensics, Cambride, MA). The five sensors were attached to the anterior aspect of each thigh, the anterior aspect of each shin, and the lower back. Gaze data were also recorded during the entirety of each 1-minute walking trial using the SMI Eye Tracking Glasses 2 Wireless (SensoMotoric Instruments, Boston, MA). These glasses collected binocular gaze orientation data (60 Hz) as calculated from pupil orientation and a digital video of the scene (30 Hz) taken from the participant’s perspective via an outward-facing camera at the nose bridge of the glasses. A separate digital video camera operated by a researcher recorded the participant’s surrounding environment during each walking trial, capturing people and objects that were both within and outside of the participant’s walking path and/or view during each trial.

The cognitive task was a category naming verbal fluency task. Category naming was chosen because it requires self-generated speech, which is cognitively demanding [40,41]. A different category was used for each trial (two single-task cognitive and two dual-task walking trials). To help control category naming difficulty across participants, all participants first performed a “calibration trial” in which they were asked to name as many animals as possible in one minute (while seated). This calibration trial also served to familiarize participants to the task. Using normative data stratified by age and education for naming animals [42], participants were assessed to be above or below the norm for their age. Participants performing at or below their age-adjusted norm were given “easy” categories and those performing above the age-adjusted norm were given “hard” categories. “Easy” and “hard” category lists were developed based on previous studies [43,44] and our own initial pilot work. Other research in our lab using these lists provides evidence that the difficulty of the categories in the two lists was appropriate [45]. The final categories are listed in Table 1. Participants were given category sets 1 and 2 for the single- and dual-task conditions in a counterbalanced order across participants, with category sets 3 and 4 reserved as backup categories if trials needed to be repeated (Table 1). Faller participants and their non-faller controls were given the category sets in the same order. During each cognitive trial, participants were instructed to name as many items as they could during the 1-minute trial. Verbal responses were recorded by a microphone in the eye-tracking glasses frame.

2.3. Data processing

For each walking trial, stride velocity (m/s), stride length (m), and stride duration (s) were recorded for each stride. Trial mean and standard deviation for each participant were calculated for each of the three gait measures with a custom Matlab (Mathworks, Natick, MA) program, employing the validated LEGSys™ algorithm [46]. On average, participants took 51 (SD 4.9) strides during each walking trial. To remove any hesitancy at the beginning of the walking trials, the first stride was omitted from the analysis if it was less than half of the magnitude of the second stride. Similarly, to control for differences in stopping at the end of the trial, the last three strides were always removed. All other strides, including turns, accelerations, and decelerations were included in the analysis to ensure that gait was representative of everyday walking and not selected for steady-state segments only. The gait dependent variables were stride length variability (coefficient of variation [CV], %), stride duration variability (CV, %), and average stride velocity (m/s). For each walking trial condition (single-task gait and dual-task walking), the values from the two trials performed were averaged for each gait variable.

Additionally for each walking trial, gaze data were analyzed using BeGaze software (SensoMotoric Instruments, Boston, MA). Within the program, the location of the gaze focal point was computed for each frame and then superimposed on the scene view to provide a frame-by-frame representation of the participant's overt attention focus. From this data, each of the participants' fixations during the walking trials were categorized as directed at one of six areas of interest (AOIs), which included: the walking path (and any objects within the walking path), people (sitting, walking or standing), and the surrounding environment (objects outside the walking path) that were then further defined as either near or far away from the participant. Near AOIs were defined as within 4-6 steps from the participant and far AOIs were defined as beyond 4-6 steps from the participant. These six AOIs, based upon categories originally defined by Foulsham et al. [47], were selected because they efficiently account for the relevant and irrelevant moving hazards and distractions that can result in falls for older adults. These AOIs have been previously described in more detail in a related study [26]. A single rater categorized all participant fixations to ensure consistency of AOI categorization across all of the participants and between trials. A custom Matlab program was then used to further post-process the gaze behavior data. Any fixations shorter than 200 ms were excluded based on previous research that showed that fixations during a visual search and while viewing a scene are at least 200 ms in duration [48]. Then the percentage of time fixating on each of the 6 AOIs out of the total 1-minute trial duration (%) and the average duration of time spent fixating on each of the 6 AOIs (ms) were computed for each trial, resulting in 12 dependent variables for gaze behavior. For each walking trial condition (single-task gait and dual-task walking), the values from the two trials performed were averaged for each of the 12 gaze behavior variables. Gaze behavior data were not analyzed during single-task cognitive trials because a number of participants closed their eyes during these trials, preventing the recording of fixation data.

For each trial involving the category naming task, the timing and appropriateness (i.e., correct fit within the category and whether or not the response was repeated) of cognitive response data were computed within the BeGaze software. Responses were then further analyzed within a custom Matlab program to calculate the three cognitive dependent variables: number of appropriate responses (#), the timing from the start of the trial to the first appropriate response (ms), and the mean subsequent response time (ms), which is the average time between the first response and each of the subsequent responses, corresponding to the amount of time that half the responses have been given [49]. A short mean subsequent response time indicates a faster decline in response retrieval and that the majority of the responses are clumped at the beginning of the trial; whereas a longer mean subsequent response time signifies that the response retrieval was more evenly dispersed throughout the trial period. For each cognitive trial condition (single-task cognitive and dual-task walking), the values from the two trials performed were averaged for each cognitive variable.

The digital video camera recordings were used to quantify the environmental busyness during each walking trial. Busyness was defined as the number of people within the participant’s field of view during each trial, including both people within and outside of the participant’s walking path. People within the participant’s field of view were manually counted during each 1-minute trial. Then the two trials for each trial condition were averaged and used in the analysis of environmental busyness.

2.4. Statistical analysis

Independent samples t-tests were used to compare the fallers and non-fallers in terms of age, gender, years of education, cognitive functioning, functional mobility, vision, and self-report community participation and balance self-efficacy. A paired samples t-test was used to compare environmental busyness encountered during single- relative to dual-task walking, and independent samples t-tests were used to compare environmental busyness between fallers and non-fallers during the two trial conditions. Repeated measures two-way (Group x Task) MANCOVAs and MANOVAs, as appropriate, were used to examine gait and cognitive-task variables. TUG, CTMT score, and the average environmental busyness were entered as covariates to control for between-group inter-individual differences. All t-tests, MANCOVAs, and MANOVAs were performed using SPSS 26 and $\alpha=0.05$. Twelve hierarchal linear regression models were created and analyzed using HLM v8.0 to examine the gaze behavior variables. Linear regressions were utilized in lieu of ANOVAs because a lot of variability was observed in the gaze behavior data, which can sometimes suppress relationships between independent and dependent variables when multiple independent variables are included in one model. Hierarchical linear modeling allows the within group effects to be separated from the between group effects. Because the independent variables were categorical, the results of the regressions can be interpreted similarly to ANOVAs. For each of the six AOIs, a regression model was run predicting average fixation duration on each AOI per trial and percentage of time fixated on each AOI per trial, respectively, from Group (fallers, non-fallers) as a Level 1 predictor variable and Trial Condition (single-task walking, dual-task walking) as a Level 2 predictor. CTMT Composite Index score, TUG score, and environmental busyness were entered as Level 2 covariates. Because percentage of time fixated on each AOI per trial is proportional data, models with this variable as an outcome were run after constricting the data to a Poisson distribution.

3. Results

3.1. Demographic characteristics and environmental busyness

Fifteen fallers and 15 non-fallers participated in the study, but technical difficulties during data collection resulted in a loss of data for several participants. One faller did not have usable cognitive, gait, or gaze behavior data, so this participant was not included in any analyses. Other participants with missing data included 1 non-faller missing gait and gaze behavior data, 1 faller missing gaze behavior data, and 1 non-faller missing gaze behavior data. These participants' missing data were not imputed and their remaining data were retained for analyses. Thus, the *n* and degrees of freedom for each analysis varied depending on how many cases were available for each variable. The analyzed sample included 14 older adult fallers (76.6±9.1 years, 11 females) and 15 older adult non-fallers (77.4±7.6 years, 11 females). As expected, the groups differed in their reported fall history, but there were no significant differences between the groups in the matched variables (age, gender, education) (Table 2). As expected, there was a significant difference in reported fall history between the fallers and non-fallers. There were also significant differences between the groups in terms of cognition, functional mobility, vision, and balance self-efficacy (Table 2), which are consistent with previous studies [17,35,36,50,51]. In terms of environmental busyness, there were no significant differences in busyness encountered during the single- and dual-task walking trial conditions or overall between trials for fallers and trials for non-fallers (Table 3).

3.2. Dual-task and group effects on gait

Results from the repeated-measures two-way MANCOVA comparing differences between fallers and non-fallers in gait variables (i.e., stride velocity, stride length CV, and stride duration CV) indicated that the CTMT score and environmental busyness covariates were not significantly related to the dependent variables. Thus, another repeated-measures two-way MANCOVA comparing differences between fallers and non-fallers in gait variables (i.e., stride velocity, stride length CV, and stride duration CV) was conducted including only TUG as a covariate. TUG was significantly related to stride velocity ($F(1, 25) = 12.312$, $p = 0.002$, $\eta_p^2 = 0.330$). The within-subjects main effect of Task was significant ($F(3, 23) = 4.538$, $p = 0.01$, $\eta_p^2 = 0.372$) because the effect of task on within-in subject differences in stride velocity was significant ($F(1, 25) = 13.063$, $p = 0.001$, $\eta_p^2 = 0.343$) (Table 4). Pairwise comparisons indicated that stride velocity was 0.21 m/s slower during dual- relative to single-task walking, but the effect was not different between fallers and non-fallers (Group by Task ($F(3, 23) = 0.572$, $p = 0.64$, $\eta_p^2 = 0.069$) (Table 4). The Task by TUG ($F(3, 23) = 1.242$, $p = 0.32$, $\eta_p^2 = 0.139$) and interaction were not significant (Table 4). The main effect for Group was not significant ($F(3, 23) = 0.548$, $p = 0.66$, $\eta_p^2 = 0.067$) (Table 4).

3.3. Dual-task and group effects on category naming

Results from the repeated-measures two-way MANCOVA examining differences between fallers and non-fallers and dual-task effects on cognitive-task variables (i.e., number of responses, time to first response, and mean subsequent response time) indicated that the CTMT score, TUG, and environmental busyness covariates were not significantly related to the dependent variables. Thus, another repeated-measures two-way MANOVA comparing differences between fallers and non-fallers in cognition variables (i.e., number of responses, time to first response, and mean subsequent response time) was conducted with no covariates. There was a significant main effect of Task ($F(3, 25) = 3.084$, $p = 0.05$, $\eta_p^2 = 0.270$) on number of responses ($F(1, 27) = 5.424$, $p = 0.03$, $\eta_p^2 = 0.167$) and mean subsequent response time ($F(1, 27) = 9.377$, $p = 0.005$, $\eta_p^2 = 0.258$) (Table 4). Pairwise comparisons indicated that participants gave 1.5 fewer responses and exhibited a 2823.0 ms shorter mean subsequent response time during dual- relative to single-task performance. The Task by Group interaction ($F(3, 25) = 1.639$, $p = 0.21$, $\eta_p^2 = 0.164$) and Group effect were not significant ($F(3, 25) = 1.193$, $p = 0.33$, $\eta_p^2 = 0.125$) (Table 4).

3.4. Dual-task and group effects on gaze behavior

Group was a significant predictor ($\beta = 70.16$, $p = 0.04$) of average fixation duration on the Far Environment per trial (Table 5). The covariate environmental busyness was a significant predictor ($\beta = 4.73$, $p = 0.009$) of average fixation duration on the Far Walking Path per trial (Table 5). There were no other significant predictors of average fixation duration on any AOI (Table 5). These results indicate that being a non-faller was associated with a longer average fixation time on the Far Environment and that a busier environment was related to a greater average fixation on the Far Walking Path.

Trial Condition (single-task walking vs dual-task walking) was a significant predictor of percentage of time fixated on Far People ($\beta = -0.164$, $p = 0.01$) and the Near Walking Path ($\beta = 0.511$, $p = 0.001$) (Table 5). Specifically, during dual-task walking, the participants fixated on Far People for a significantly smaller percentage of time and on the Near Walking Path for a significantly greater percentage of time than during single-task walking. The covariate CTMT Composite Index score was a significant predictor ($\beta = -0.036$, $p = 0.03$) of percentage of time fixated on the Far Walking Path per trial, the covariate TUG score was a significant predictor of percentage of time fixated on Far People ($\beta = 0.129$, $p = 0.03$), and the covariate environmental busyness was a significant predictor of percentage of time fixated on the Near Walking Path ($\beta = -0.050$, $p = 0.05$) (Table 5). These results indicate that a higher CTMT score (better performance) is related to a smaller percentage of time fixating on the Far Walking Path, a higher TUG score (worse performance) is related to a greater percentage of time fixating on Far People, and that a busier environment is related to a smaller percentage of time fixating on the Near Walking Path.

4. Discussion

The purpose of this project was to investigate how dual tasking may impact gait, visual scanning (gaze), and cognitive performance in older adult fallers and non-fallers in a real-world environment. In terms of gait, after adjusting for baseline TUG scores as a measure of functional mobility, participants walked 0.21 m/s slower during dual- relative to single-task walking, in agreement with our primary hypothesis. These results are consistent with previous research that observed older adults to walk more slowly with the addition of a 3-back working memory test [11]. While the results are similar, the effect size observed in the present study ($\eta_p^2 = 0.372$) was much larger than the effect size observed in Schaefer et al. [11] ($\eta_p^2 = 0.118$). This difference may point towards a verbal fluency task, like category naming or having a conversation, impacting gait more than a working memory task or a real-world environment producing a greater dual-task effect on gait than a lab environment. The difference may also be attributed to, at least in part, the fact that Schaefer et al.'s [11] participant sample included younger and older adults, while our participant sample included older adults only. In contrast to our hypothesis, after adjusting for baseline TUG scores, the Group by Task interaction for gait speed was not significant, despite observing that fallers demonstrated a 0.23 m/s dual-task decline in gait speed compared to 0.19 m/s for non-fallers. This difference in dual-task cost on gait speed in fallers relative to non-fallers is interesting because the difference, although not significant, falls within the range of small effects for meaningful gait speed change in older adults (0.04-0.06 m/s) [52]. This discrepancy may indicate that the intra-group variability of the fallers and non-fallers groups, specifically a few really fast and slow walkers in each group, caused variance overlap between the groups and thus suppressed the inter-group differences. Of note, the non-significant difference in dual-task cost on gait speed between fallers and non-fallers is in agreement with previous findings by Freire Júnior et al. [53] who observed fallers to walk 0.19 m/s more slowly and non-fallers to walk 0.21 m/s more slowly during dual- relative to single-task walking. Although Freire Júnior et al. [53] used the same category naming task as the present study, their testing was performed in a quiet, laboratory environment and is thus not entirely comparable.

In terms of cognitive performance, for which there were no significant covariates, all participants gave 1.5 fewer appropriate responses and exhibited a 2823.0 ms shorter mean subsequent reaction time during dual- relative to single-task performance (Table 4). The co-occurrence of these dual-task effects is notable because they indicate a definite dual-task performance decrement on cognition for all participants. Indeed, the solitary occurrence of either a decline in number of responses given or a shorter mean subsequent reaction time (i.e., a faster decline in response retrieval rate) could have been offset by dual-task performance improvements, such as a longer mean subsequent reaction time (i.e., a more evenly dispersed response retrieval throughout the trial period) or a greater number of responses given, respectively [54], resulting in either no net change in overall dual-task performance or even a dual-task performance benefit. Thus, again, the co-occurrence of fewer responses given and a faster decline in response retrieval rate indicate that all participants exhibited a dual-task performance cost on cognition in addition to a dual-task cost on gait.

In agreement with our hypothesis, dual-task walking was associated with a greater percentage of time fixating on the Near Walking Path and a smaller percentage of time fixating on Far People, relative to single-task walking. As expected, participants increased the relative amount of time that they fixated on the Near Walking Path from single- to dual-task walking, likely in order to better focus on the cognitive task and to facilitate safely navigating their immediate walking path in the hospital lobby. More specifically, participants may have focused on the floor immediately in front of them in order to ensure that their walking path remained unobstructed while simultaneously providing for themselves blank floor space to stare at to reduce environmental distractions and improve concentration during performance of the cognitive task. These findings are compatible with our related work that demonstrated older adult participants increased the percentage of time that they fixated on Near and Far People while reducing the percentage of time that they fixated on the Near and Far Walking Path during single-task walking in a busy environment, relative to in a quiet, distraction-free lab setting [26]. Because the environmental and task demands differed between the two studies, the different directions of change in visual attention are not incongruent. We attributed the results of our previous study to age-related declines in central processing that have been shown to result in longer fixation durations on obstacles to be avoided, such as bystanders and pedestrians in the environment, and age-related declines in the ability to ignore distractions, such as those same dynamic bystanders and pedestrians [26,55,56]. Similarly, in the current study, participants may have had difficulty concentrating on the cognitive task during the dual-task walking condition because bystanders and pedestrians in the environment were a source of distraction that were hard to ignore. Participants may have thus selected to narrow their scan field to the walking path immediately in front of them, in order to prioritize performing the category naming task, even though, regardless, performance on the cognitive task and gait speed declined during dualrelative to single-task conditions. This shift in visual attention to the walking path immediately in front of them while simultaneously walking and performing a cognitive task in a distracting, real-world environment is significant because it could indicate that older adults are limited in their ability to plan their more distant walking trajectory and may have limited time to react to and try to avoid a potential hazard that appears in the walking path, both of which limitations could negatively impact walking safety.

Regardless of task condition, as the hospital lobby became busier, participants fixated for a smaller percentage of time on the Near Walking Path and for longer average durations on the Far Walking Path, appearing to shift their attention farther out from their base of support and immediate surroundings. We interpret these findings to suggest that when the environment was less busy, participants were able to occasionally gaze at their farther surroundings, possibly planning their walking trajectory to avoid pedestrians and stationary furniture, and then refocus their gaze on the walking path immediately in front of them. Whereas, when the environment was busier, participants may have had to more frequently update their navigation plan to avoid collisions with moving pedestrians or objects in the walking path. This interpretation is consistent with previous research demonstrating that when individuals walk in more complex and unpredictable environments they are less able to rely upon their working memory of spatial locations of potential obstacles and must fixate on an object more often, especially when the object is highly relevant or its spatial location is uncertain from one moment to the next [25,57]. Additionally, these results underscore the potential implications of older adults directing less attention to the Far Walking Path and Near and Far People in the environment when concentrating on a cognitive task and walking, such as chatting while walking with a companion.

Finally, relative to fallers, being a non-faller was associated with a longer average fixation time on the Far Environment, which was comprised of the artwork and stationary furniture of the hospital lobby that were far outside of the walking path. Longer fixation times on the Far Environment are indicative of non-fallers acquiring and storing into memory more visual information than fallers about items in the environment that were least relevant to walking safety [58]. Although a seemingly small group difference, a longer fixation time on the Far Environment may suggest that non-fallers are more comfortable than fallers in directing their attention away from potential hazards in their walkway to visual stimuli that are interesting but irrelevant to safe walking. These results are in agreement with our related work that similarly demonstrated non-fallers to fixate for longer durations on the Near Environment than fallers while single-task walking in a busy environment [26]. Additionally, although not explicitly group differences, there were relationships between two indicators of fall risk and specific patterns of gaze behavior. Specifically, the worse a participant’s TUG performance, the larger percentage of time that participant spent fixating on Far People, and the worse a participant’s CTMT score, the larger percentage of time that participant spent fixating on the Far Walking Path. These results suggest that while both declines in functional mobility and executive function are associated with a higher risk of falling [50,59], mobility and cognitive deficits may influence patterns of gaze behavior and strategies for navigating complex environments in older adults in different ways, and thus functional mobility and executive function deficits may be associated with falls for different reasons. Specifically, those with a greater functional mobility deficit may have spent a greater percentage of time fixating on Far People in order to more fully process where potential obstacles were or, alternatively, may have adopted a strategy of walking more slowly in order to have more time to process potential obstacles. Along the same line, those with a greater executive function deficit may have spent a greater percentage of time fixating on the Far Walking Path, in an effort to avoid distractions, such as people or the irrelevant environment around them. Regardless of the exact reason why certain deficits or fall status resulted in specific gaze behavior strategies, these results highlight the multifactorial nature of falls and indicate that gaze behavior should be further explored in relation to falls in older adults.

4.1. Limitations

This study has some limitations. First, the study is limited by a small sample size. The HLM analysis was specifically used to analyze the gaze data because it uses a hierarchical structure, which allows you to determine the order of importance of the factors and thus helps to reduce the influence of variability within the dataset. Therefore, the statistical analysis chosen mitigated the impact of a small sample size for the gaze data. The observed power for the gait and cognitive analyses ranged from $\beta = 0.145 – 0.822$, with higher power values for comparisons of the trial conditions and lower power values for group comparisons. Thus, the significant results of this study are not likely due to chance and remain important to report, but there may be other significant differences in gait and cognition between fallers and non-fallers that were not illuminated. Second, the pedestrian traffic was uncontrolled from participant to participant in order to maximize ecological validity of the testing. The environmental busyness t-tests, however, provided evidence that there were no differences in busyness encountered between the trial conditions across participants or between the fallers and non-fallers groups. Additionally, environmental busyness was entered as a covariate in all of the cognitive performance, gait, and gaze behavior analyses, ensuring that slight differences in pedestrian density experienced by different participants did not skew the results.

5. Conclusions

The results of this study demonstrate that dual tasking negatively impacts gait and cognitive performance and causes a shift in gaze behavior. Therefore, examining dual-task performance in older adults is critical to understanding how they will or will not be able to perform activities of daily living. In terms of group differences, non-fallers direct their gaze to less relevant environmental stimuli for longer durations than fallers. Additionally, the occurrence of two fall risk indicators, a slow TUG performance and a lower score on the CTMT, predicts two different shifts in gaze behavior, respectively, and the busyness of the environment similarly impacts gaze behavior. These results suggest that fall status, functional mobility deficits, and executive function declines may impact real-world walking differently, and the distractions and unpredictability of the real world have an important effect on how older adults attend to their environment while walking. Overt visual attention during walking in real-world environments should be further explored in relation to fall risk.

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Highlights

- Dual-tasking impacts gait, gaze, and cognitive performance in older adults
- Fallers exhibit different gaze behavior than non-fallers in a real-world setting
- Overt visual attention while walking is impacted by different measures of fall risk

Table 1.

Category sets for each trial condition.

Easy Categories	Hard Categories
Set 1	**Set 1**
Items of furniture/clothing	Musical instruments
Sports Equipment	Canned goods/things that come in a jar
Set 2	**Set 2**
Things you would see at a theme park	Colors
Things you would see at a restaurant	Well-known/famous people
Set 3	**Set 3**
Fruits/vegetables	Building Materials
Things you would see at the beach	Appliances/other electronics
Set 4	**Set 4**
Body parts	Birds
Occupations	Tools

Table 2.

Characteristics of the participants in each group. P-values represent the independent samples t-tests.

Values are Mean±SD or Median(IQR).

	Fallers (n=14)	Non-fallers (n=15)	p-value
Demographic Characteristics			
Age (years)	76.6±9.1	77.4±7.6	p=0.79
Gender	3 males, 11 females	4 males, 11 females	p=0.75
Years of Education	16.9±3.2	16.9±2.4	p=0.98
Number of Falls in Last 12 Months	2 (2 – 4)	0 (0 – 0)	**p<0.001**
Cognitive Assessments			
Montreal Cognitive Assessment (max. 30)	26.2±2.5	27.0±2.3	p=0.35
WAIS Vocabulary Subtest (max. 70)	56.5 (54 – 60)	59 (57 – 62)	p=0.09
WAIS Digit Symbol Substitution Subtest (max. 93)	41.2±9.9	51.5±7.3	**p=0.003**
WAIS Digit Symbol Copy Subtest (sec)	89.1 (76.2 – 112.0)	75.8 (68.5 – 87.1)	**p=0.04**
Comprehensive Trail Making Test Composite Index	44.0±6.8	54.3±5.6	**p<0.001**
Stroop Color-word Test Interference Reaction Time (ms)	445.3±136.9	324.4±101.1	**p=0.01**
Functional Mobility Assessments			
10 Meter Walk Test (m/s)	1.08±0.27	1.30±0.17	**p=0.01**
Timed Up and Go (sec)	9.7 (8.2 – 13.2)	7.9 (7.1 – 8.4)	**p=0.003**
Four Square Step Test (sec)	12.8 (7.7 – 16.7)	8.9 (8.7 – 9.4)	**p=0.01**
Dynamic Gait Index (max. 24)	19.5 (17 – 22)	23 (23 – 24)	**p=0.001**
Vision Assessments			
Snellen Vision Acuity (with corrective lenses, normal is 20/20)	20/40 (20/70 - 20/25)	20/20 (20/40 - 20/20)	**p=0.01**
Melbourne Edge Test of Contrast Sensitivity (max. 24)	19 (18.75 – 20)	20 (20 – 21)	p=0.08
Community Participation and Self-Efficacy			
Physical Activity Scale for the Elderly	132.1±59.0	147.7±77.2	p=0.55
Activities-Specific Balance Confidence Scale (max. 100)	82.5 (59.1 – 87.6)	91.9 (89.1 – 97.5)	**p=0.005**

Table 3.

Busyness in the environment by condition and group. P-values represent the independent and paired samples t-tests.

Values are Mean±SD.

	Environmental Busyness (number of individuals)		**p-value**
Single-Task Walking(n=29)	22.9±7.6		p=0.45
Dual-Task Walking(n=29)	22.0±6.8		
	Environmental Busyness (number of individuals)		**p-value**
	Fallers (n=14)	**Non-fallers (n=15)**	
Single-Task Walking	22.5±8.7	23.3±6.8	p=0.78
Dual-Task Walking	19.7±5.7	24.2±7.2	p=0.08

Table 4.

Average walking and category naming performance for fallers and non-fallers during single- and dual-task performances.

Gait values are adjusted (for TUG) Mean±SE and cognitive values are unadjusted Mean±SE.

	Fallers (n=14)	Non-fallers (n=14)
Stride Velocity (m/s)		
Single-Task Walking	**1.21 ± 0.05** *	**1.25 ± 0.05** *
Dual-Task Walking	**0.98 ± 0.05** *	**1.05 ± 0.05** [a]
Stride Length CV (%)		
Single-Task Walking	11.41 ± 0.89	11.24 ± 0.89
Dual-Task Walking	10.9 4 ± 0.75	9.23 ± 0.75
Stride Duration CV (%)		
Single-Task Walking	6.28 ± 1.11	7.08±1.11
Dual-Task Walking	6.01 ± 1.09	6.79 ± 1.09
	Fallers (n=14)	**Non-fallers (n=15)**
Number of responses (#)		
Single-Task Seated	**14.1 ± 1.2** *	**18.0 ± 1.1** *
Dual-Task Walking	**13.7 ± 1.3** *	**15.4 ± 1.2** *
Time to first response (ms)		
Single-Task Seated	2477.4 ± 396.1	2352.3 ± 382.7
Dual-Task Walking	2808.2 ± 265.7	2049.4 ± 256.7
Mean subsequent response time (ms)		
Single-Task Seated	**21019.5 ± 1029.3** *	**22603.9 ± 994.4** *
Dual-Task Walking	**18144.6 ± 1147.7** *	**29832.6 ± 1108.8** *

*Indicates a significant Task difference at the α=0.05 level

Table 5.

HLM estimates of group, trial condition, and covariates (environmental busyness, CTMT, and TUG) as predictors of average fixation duration on each AOI and percentage of time fixating on each AOI.

	Average Fixation Duration			Percentage of Time Fixating		
	Coefficient	**Standard Error**	***t*-ratio**	**Coefficient**	**Standard Error**	***t*-ratio**
Far Environment						
Group	**70.155**	**31.592**	**2.22** *	0.687	0.377	1.82
Trial Condition	−22.515	24.520	−0.92	−0.085	0.133	−0.64
Environmental	2.303	1.774	1.30	0.013	0.021	0.63
Busyness	−2.730	1.943	−1.41	−0.004	0.024	−0.146
CTMT	12.724	8.195	1.55	0.092	0.080	1.15
TUG						
Far Walking						
Group	49.830	28.508	1.75	0.467	0.252	1.86
Trial Condition	19.991	23.511	0.85	0.058	0.068	0.85
Environmental	**4.728**	**1.654**	**2.86** **	−0.017	0.014	−1.21
Busyness	−1.923	2.092	−0.92	**−0.036**	**0.016**	**−2.27** *
CTMT	14.763	8.451	1.75	−0.031	0.053	−0.60
TUG						
Far People						
Group	30.468	29.836	1.02	0.039	0.249	0.16
Trial Condition	5.236	12.810	0.41	**−0.164**	**0.059**	**−2.78** *
Environmental	1.455	2.093	0.70	0.023	0.014	1.60
Busyness	−1.338	2.623	−0.51	0.008	0.016	0.52
CTMT	14.307	10.122	1.41	**0.129**	**0.054**	**2.41** *
TUG						
Near Environment						
Group	106.368	77.472	1.37	1.625	1.048	1.55
Trial Condition	22.938	75.455	0.30	−0.253	0.541	−0.47
Environmental	1.706	4.657	0.37	−0.027	0.047	−0.59
Busyness	7.551	6.068	1.24	0.033	0.052	0.64
CTMT	29.211	26.653	1.10	0.232	0.207	1.12
TUG						
Near Walking						
Group	−28.212	63.457	−0.45	−0.231	0.411	−0.56
Trial Condition	−16.818	54.053	−0.31	**0.511**	**0.139**	**3.69** **
Environmental	−0.229	3.098	−0.07	**−0.050**	**0.024**	**−2.10** *
Busyness	0.088	3.529	0.03	−0.012	0.027	−0.45
CTMT	−3.676	10.102	−0.36	−0.075	0.088	−0.85
TUG						

	Average Fixation Duration			Percentage of Time Fixating		
	Coefficient	**Standard Error**	***t*-ratio**	**Coefficient**	**Standard Error**	***t*-ratio**
Near People						
Group	−17.903	54.297	−0.33	−0.042	0.467	−0.09
Trial Condition	−54.892	41.047	−1.34	−0.466	0.279	−1.67
Environmental	4.719	2.776	1.70	0.022	0.027	0.81
Busyness	3.820	3.169	1.21	0.047	0.030	1.58
CTMT	20.106	10.385	1.94	0.190	0.097	1.95
TUG						

*Indicates significance at p<0.05

**Indicates significance at p<0.01