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# Reduced Vision Selectively Impairs Spatial Updating in Fall-prone Older Adults

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**Abstract**

The current study examined the role of vision in spatial updating and its potential contribution to an increased risk of falls in older adults. Spatial updating was assessed using a path integration task in fall-prone and healthy older adults. Specifically, participants conducted a triangle completion task in which they were guided along two sides of a triangular route and were then required to return, unguided, to the starting point. During the task, participants could either clearly view their surroundings (full vision) or visuo-spatial information was reduced by means of translucent goggles (reduced vision). Path integration performance was measured by calculating the distance and angular deviation from the participant's return point relative to the starting point. Gait parameters for the unguided walk were also recorded. We found equivalent performance across groups on all measures in the full vision condition. In contrast, in the reduced vision condition, where participants had to rely on interoceptive cues to spatially update their position, fall-prone older adults made significantly larger distance errors relative to healthy older adults. However, there were no other performance differences between fall-prone and healthy older adults. These findings suggest that fall-prone older adults, compared to healthy older adults, have greater difficulty in reweighting other sensory cues for spatial updating when visual information is unreliable.

**Keywords**

Multisensory processing, ageing, spatial updating, path integration, falls, gait

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## 1. Introduction

The ability to update one's location whilst navigating through an environment is dependent on complex interactions between multisensory (e.g. Klatzky *et al.*, 1998; Tcheang *et al.*, 2011), motor (Dingwell and Cusumano, 2000; Hansen *et al.*, 2001) and cognitive processes (Regnaux *et al.*, 2006; Shumway-Cook *et al.*, 1997; Woollacott and Shumway-Cook, 2002). Although many studies have investigated the role of these processes in young adults, relatively less is understood about how ageing affects efficient spatial updating during locomotion (for reviews see e.g. Klencklen *et al.*, 2012; Moffat, 2009). Furthermore, ageing is associated with an increase in the risk of falling (Stevens *et al.*, 2008). Here we investigated whether falls in older adults may be associated with inefficient spatial updating during navigation, by comparing path integration across fall-prone and healthy older adults using a triangle completion task. Also, we explicitly tested the role of vision in this task by comparing performance across both older adult groups under full and reduced visual conditions.

Destination-guided locomotion requires the constant updating of one's position in relation to the surroundings. Spatial updating is a cognitive process which subserves effective navigation, when the target destination is not perceivable during locomotion (Klier and Angelaki, 2008; Loomis *et al.*, 1999; Mou *et al.*, 2006; Wolbers and Hegarty, 2010; Wolbers *et al.*, 2008). Efficient updating of spatial information relies on optimally combining input from sensory systems, such as vision and the vestibular system (Durgin, 2009; Durgin *et al.*, 2005a, 2005b), vision and haptics (Pasqualotto and Newell, 2007) and vision and audition (Loomis *et al.*, 2002). Exteroceptive cues can provide information about the location of external landmark cues during self-motion (Allen *et al.*, 2004; Etienne and Jeffery, 2004; Nardini *et al.*, 2008; Rump and McNamara, 2007), and interoceptive cues from the vestibular system, kinaesthetics and proprioception provide information about the velocity, acceleration, orientation and heading direction of one's body (Allen *et al.*, 2004; Angelaki and Cullen, 2008; Angelaki and Hess, 2005; Au Yong *et al.*, 2007; Butler *et al.*, 2010). In order to optimally combine different information from across these sensory systems, the reliability of the inputs must be ascertained (Cheng *et al.*, 2007; Deneve and Pouget, 2004; Fetsch *et al.*, 2010). For example, when sensory information about the environment from one modality is reduced, it is necessary to reweight other sensory information in order to compensate for this reduction and to maintain efficient spatial updating (Klier and Angelaki, 2008; Loomis *et al.*, 1999; Mou *et al.*, 2006; Wolbers and Hegarty, 2010; Wolbers *et al.*, 2008).

Despite multisensory contributions to spatial cognition, visual information can play a crucial role in the perception of self-motion (Britten, 2008; Durgin, 2009; Klier and Angelaki, 2008), self-acceleration (Ishida *et al.*, 2008), locomotor processes (Patla, 1997) and navigation over long distances (Souman *et al.*, 2009). Indeed, it has been suggested that older adults are relatively more reliant on visual cues during locomotion than other sensory inputs (Anderson *et al.*, 1998). Moreover, visual impairment is identified as a key contributor to falls risk in older adults (Abdelhafiz and Austin, 2003; Harwood, 2001; Lord and Dayhew, 2001).

The interplay between multiple sensory systems may enable the central nervous system (CNS) to resolve potential ambiguity arising from either unreliable or reduced sensory input (see e.g. Allen *et al.*, 2004; Frissen *et al.*, 2011; Klatzky *et al.*, 1990). For example, perception may benefit from combining sensory information, even when the information from each modality is uncertain, known as the 'inverse effectiveness' effect (Stein and Meredith, 1993). Indeed, previous studies have provided evidence that vestibular and proprioceptive information are sufficient to navigate simple routes through the environment when visual information is absent (Fukusima *et al.*, 1997; Klatzky *et al.*, 1990; Loomis *et al.*, 1993; Tcheang *et al.*, 2011). Similarly, the visual and somatosensory systems have been known to compensate for the lack of vestibular information in patients with vestibular loss (Dieterich *et al.*, 2007; Strupp *et al.*, 1998). These studies suggest that the CNS is robust to long-term deficits in a single sensory modality by compensating this information with more reliable inputs. This compensation may particularly apply to the maintenance of robust perception in older adults since healthy ageing is accompanied by declines in visual (Andersen, 2012; Owsley, 2011), proprioception (Goble *et al.*, 2009; Shaffer and Harrison, 2007), and vestibular function (Baloh *et al.*, 2003; Furman and Redfern, 2001; Takei *et al.*, 1996).

There is, however, evidence to suggest that older adults are slower to adapt to incidental changes in visual (Berard *et al.*, 2009; O'Connor *et al.*, 2008), vestibular (Deshpande and Patla, 2007), and proprioceptive (Hay *et al.*, 1996) input compared to younger adults. The discrepancy between younger and older adults in responding to changes in information from the different senses may be indicative of a general age-related decline in efficient cross-sensory compensation or reweighting (e.g. Diederich *et al.*, 2008; Poliakoff *et al.*, 2006; Setti *et al.*, 2011). Moreover, a relatively larger decline in cross-sensory reweighting specific to locomotion has been associated with an increased risk of falling in older adults (Newell *et al.*, 2011; Tang and Woollacott, 1998). It is possible, therefore, that processing ambiguous sensory input may lead to inaccurate spatial updating which may place the older population at increased risk of falls (Sturnieks *et al.*, 2008).

It is estimated that approximately 30% of adults over the age of 60 years fall at least once each year (Kenny *et al.*, 2009; Tinetti *et al.*, 1988). The incidence of falls in the ageing population is a major cause of concern due to the impact injuries have on curtailing the independence of older adults (Gill *et al.*, 2001; Tinetti and Williams, 1998; Todd and Skelton, 2004) and on the overall socio-economic impact of the cost of associated health care. Falls are also identified as being the most common cause of injury-related deaths for people over 65 years of age (Kenny *et al.*, 2009; Stevens *et al.*, 2008). Although there are many risk factors associated with falls, including frailty, deficits in lower limb proprioception (Rossat *et al.*, 2010), and loss of balance control control (Sturnieks *et al.*, 2008; Tinetti *et al.*, 1988), none of these risk factors alone contribute to a fall and the underlying cause of falls in older people is still poorly understood. In particular, although multisensory processing is involved in spatial cognition, little is known about whether inefficient multisensory integration may contribute to impaired spatial processing in older persons with a history of falls. A better understanding of the role of multisensory integration on balance control and locomotion may help identify biomarkers for determining risk of falling and may also impact on the design of intervention programmes targeted at reducing the incidence of falls.

Previous studies have suggested that certain gait parameters have been related to increased falls risk in older adults (Maki, 1997; Topper *et al.*, 1993; Verghese *et al.*, 2009, 2010). For example, Chou *et al.* (2009) found that older adults walked more slowly and had decreased stride length relative to younger adults when blindfolded, although there were no such differences observed under conditions in which full visual (optic flow) information was available. In a prospective study on falls and fear of falling in the older population, Maki (1997) found that increased variability in stride length and stride velocity were associated with a future incidence of falling whereas reduced stride length and stride velocity were associated with a fear of falling only. Verghese *et al.* (2009) also found that increased stride length variability was associated with increased risk of falls but, in contrast to Maki (1997), they found that reduced stride velocity was also a predictor of falling. Although these studies provide evidence of altered gait patterns in fall-prone older adults, it is unclear whether perceptual processes can contribute to these differences in motor output. However, in a preliminary study, Newell *et al.* (2011) measured gait velocity with 5 fall-prone participants during a path integration task, using gait sensors embedded in a floor mat (‘Gaitrite’ mat). They reported a positive correlation between increased stride velocity and increased distance error for fall-prone older adults, suggesting that inefficient updating of spatial information during locomotion may contribute to falls risk in older adults.

In the following study, spatial updating was assessed by measuring path integration in a large-scale, triangular completion task. The aim of the study was to compare path integration during locomotion across two older adult groups, healthy and fall-prone. Furthermore, we assessed the role of vision in updating spatial information during locomotion by conducting the task under two different visual conditions: participants could either view their surroundings (full vision), or visual cues were obscured (reduced vision condition), as visual impairment is associated with falls risk in older adults (Abdelhafiz and Austin, 2003; Harwood, 2001; Lord and Dayhew, 2001). Gait parameters were obtained using wearable technology which allowed the measurement of a number of stride variables. If fall-prone older adults have impaired spatial updating when visual input is ambiguous, as suggested by previous studies (Newell *et al.*, 2011), we expected these older adults to make more errors than age-matched healthy adults in estimating the location of the start point on a triangular completion task in the reduced visual condition. Finally, we expected that gait patterns such as stride velocity would differ between groups as previous studies have found that stride velocity (Verghese *et al.*, 2009) and variability in stride length and stride velocity (Maki, 1997; Verghese *et al.*, 2009) were associated with falls in older adults.

## 2. Method

### *2.1. Participants*

We recruited 25 older adults with a history of recurrent falls and 22 older adults with no history of falling through the Technology Research for Independent Living (TRIL) project hosted by St. James' Hospital Dublin. Of these 47 participants, data from 8 participants were not included for the following reasons: 2 participants had a Mini Mental State Exam (MMSE) score below our inclusion criterion of 25 and above, 1 participant suffered from Parkinson's Disease, 1 participant had recently undergone surgery for cataract removal, and another suffered from osteoarthritis. Data from 1 other participant were not included as they did not complete the task and data from a further 2 participants were lost due to technical problems with the sensor equipment. The remaining 39 participants were community dwelling, older adults with no history of psychiatric or neurological illness and had normal or corrected to normal vision. Participants had acceptable hearing (14 in fall-prone and 14 in the healthy older groups), or a mild hearing impairment (5 in fall-prone, and 6 in the healthy older adult groups), as measured by the Hughson-Westlake method. This final sample of participants comprised 19 older adults with a history of recurrent falls (3 male, 16 female) and 20 healthy older adults (6 male, 14 female) with no history of falling.

Participants were assessed on a number of measures known to be associated with falls risk (see Table 1). The two groups were matched across age and scored in the normal range on cognitive ability, as measured by the MMSE. Muscle strength was measured by averaging grip strength across the left and right hand. Balance control was assessed by both the 'Timed Up and Go'

**Table 1.**
Results (i.e. mean, standard deviation, and $t$-test comparisons) for each of the characteristics tested across the fall-prone and healthy older adult groups

| | Fall-prone older group | | Healthy older group (no falls) | | $t$-Tests |
|---|---|---|---|---|---|
| | *Mean* | *SD* | *Mean* | *SD* | *P* |
| Age | 73.42 | 4.8 | 72.9 | 5.7 | 0.76 |
| MMSE | 27.95 | 1.43 | 28.3 | 1.56 | 0.47 |
| Grip | 45.94 | 14.23 | 49.68 | 20.11 | 0.51 |
| TUG | 10.21 | 1.76 | 10.08 | 2.33 | 0.84 |
| BERG | 54.53 | 2.41 | 55.3 | 1.08 | 0.21 |
| LogMar | 0.0247 | 0.084 | 0.023 | 0.092 | 0.95 |
| Contrast sensitivity | 1.7 | 0.101 | 1.71 | 0.104 | 0.64 |
| MFES | 9.6 | 0.73 | 9.8 | 0.65 | 0.27 |

(TUG) test, and by the 'Berg Balance' Scale. We also measured sensory acuity in vision (using the Pelli-Robson contrast sensitivity test and the LogMAR chart). Finally, we assessed fear of falling using the Modified Falls Efficacy Scale (MFES) which has previously been associated with increased risk of falls in the older population (Todd and Skelton, 2004). Performance across the fall-prone and healthy older adult groups was compared using independent samples $t$-tests which revealed no differences for characteristics associated with falls risk, and both groups functioning within normal ranges on these tasks (see Table 1). As our results suggested normal (i.e. age-appropriate) function for the older participants in our sample, and no differences across groups, these findings ensured that outcome measures were not due to underlying cognitive, motor or sensory differences between groups (see Note 1).

Participants were categorised as 'fall-prone' if they had fallen at least twice in the last five years, and if the fall was not typically explained by environmental hazards. As such, our study complied with the WHO definition of a fall as 'an event which resulted in a person coming to rest on the lower level regardless of whether an injury was sustained, and not as a result of a major intrinsic event or environmental hazard' (Todd and Skelton, 2004). A nurse, trained in gerontology, determined faller status following an in-depth interview with each participant. In the 'fall-prone' group, 15 participants experienced a fall within the 18 months prior to participating in the current study whereas the remaining 4 fall-prone participants experienced their most recent fall more than 18 months prior to testing. A participant was categorised as a healthy older adult (or 'non faller') if they had no history of falling in the previous five years, or reported a single fall which was clearly explained by the presence of an environmental hazard (e.g. slipped on ice) and subsequently classified as an accidental fall (Morse, 2009). In the group of healthy non-fallers, 15 had no falls history in the last 5 years and 5 had one accidental fall within the last 5 years. Only one non-faller required medical attention as a result of a fall due to an environmental hazard.

### 2.2. Apparatus

The study was conducted in a testing room located in St. James' Hospital, Dublin (see Fig. 1 for a schematic illustration of room layout). The room measured 5.7 by 8 m and was lit by natural lighting from four windows. In one of the experimental conditions, the 'reduced vision' condition, participants were required to wear translucent goggles which consisted of safety goggles covered in packaging tape. The goggles reduced the intensity of light by 95 lux (lumen per square metre) which allowed for the perception of light from the windows (although this was minimal) but obscured other visuo-spatial information in the scene including the location of landmarks such as the door or items of furniture (e.g. a table or chairs).

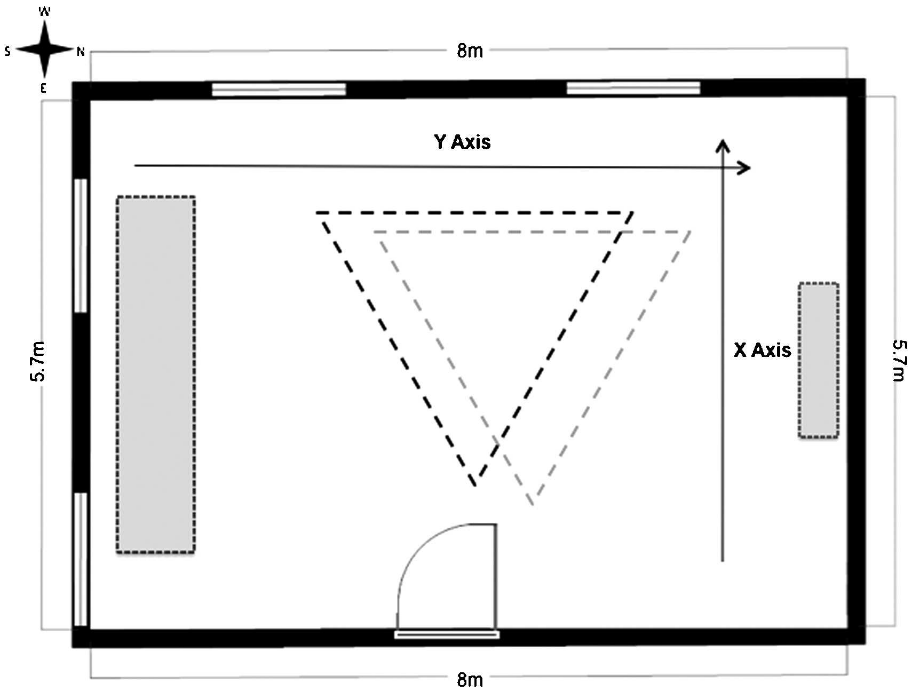


**Figure 1.** Schematic illustration of the testing room. The path along which the participant walked is marked by dashed lines. There were two locations of this triangular pathway (indicated by dark and lighter versions) tested. There were four windows in the room. Items of furniture, e.g. chairs, were also present in the room and were positioned within the area shaded in grey to the left of the figure.

The task utilised in this study, known as the triangle completion task, was adapted from previous studies (e.g. Klatzky *et al.*, 1998; Loomis *et al.*, 1993; Worchel and Mauney, 1951). A triangular pathway was covertly marked on the floor of the testing room (using tape which was invisible to the participant) and the task for the participant was to walk along this route, guided along two sides and then return, unguided, to the start point (see Fig. 2 for an illustration).

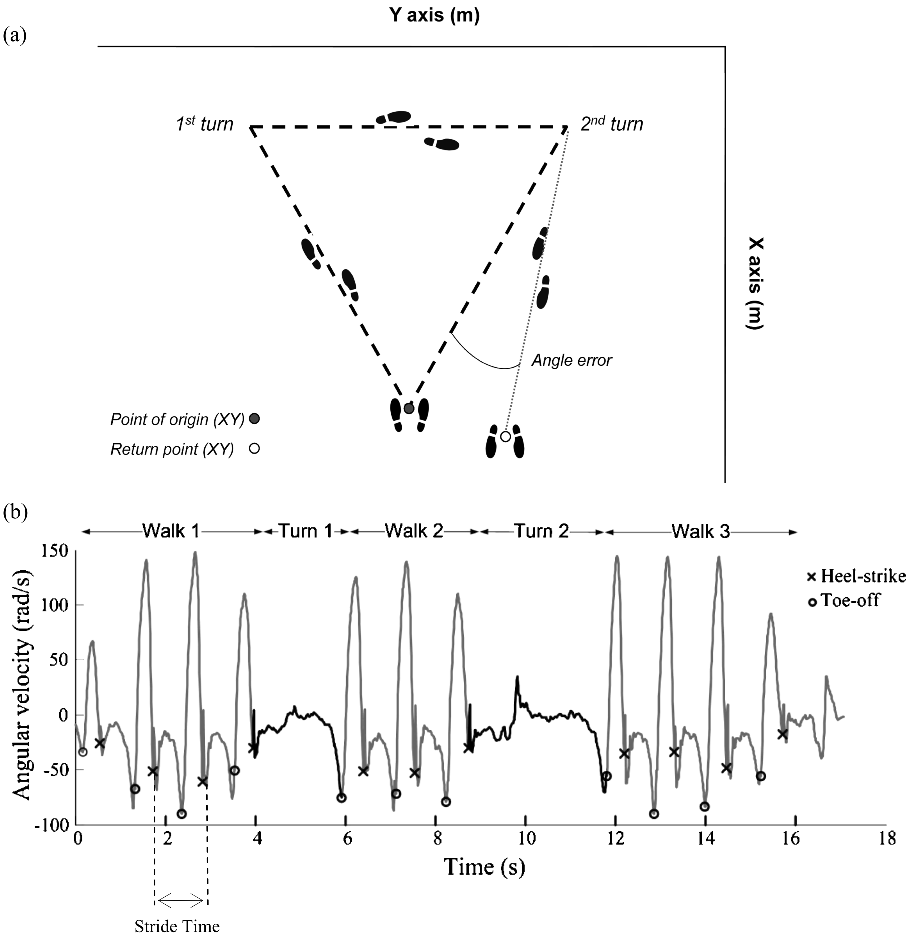


**Figure 2.** (a) Schematic illustration of a triangular walk in which the participant was guided along two sides of the path (until the 2nd turn) and were then required to return, unguided, to the start point. This illustration provides an example of performance during the 'reduced vision' condition in which a large angle error was made (as shown by the direction of footprints). (b) An example of angular velocity recorded from a 70 year old female participant during the triangular walk (derived from the gyroscope signal), in a trial in the 'reduced vision' condition. Each heel-strike and toe-off is indicated, and the segmentation of the task into three walking sections and two turns is illustrated.

To reduce explicit navigational strategies being adopted by the participant, we randomised the start point across trials and we used two different triangular pathways (based on the same dimensions) that were mislocated relative to each other by about 30 cm (see Fig. 2(a)). We randomly assigned the order of each pathway across trials for each participant. Each side of the triangle path measured 3 m. The position of each triangle vertex was defined by X and Y coordinates relative to two walls of the room (i.e. coordinates $X = 1.7$, $Y = 6.2$ were 1.7 m distance perpendicular to the west-facing wall and 6.2 m distance perpendicular to the north-facing wall respectively, as shown in Fig. 2(a)) and was measured using a laser distance measure (Bosch DLE 70 Professional). The laser measuring device was also used to record the X, Y coordinates of each participant's final return position (again defined as relative to the distance from the west-facing and north-facing walls) taken from the mid-point between the participant's feet (see Fig. 2(a) for an example).

Participants wore wireless inertial sensors (SHIMMER, Realtime Ltd. Dublin, Ireland) containing tri-axial gyroscopes that recorded kinematic movement and gait patterns during walking. The sensors were attached to the mid-point of the left and right anterior shank and held in position with compression stockings. Data during walking were streamed to a laptop *via* Bluetooth and recorded using Biomobius software 2.0 (www.biomobius.org). Sensors were oriented to capture the rotation of the shank in the sagittal plane. Gyroscope data were sampled at 102.4 Hz, and were subsequently used for the detection of gait patterns.

### 2.3. Design

The experimental protocol consisted of a two-way, mixed design with participant group (fall-prone and healthy older adults) as the between-subjects factor and visual condition (full or reduced vision) as the within-subjects factor. Trials were separated into two blocks based on the visual conditions and block order was counterbalanced across participants.

Each participant performed two blocks of 6 trials. In one block, participants could view their surroundings (the full vision condition) during navigation and in the other block (the reduced vision condition) participants wore translucent goggles which obscured landmark information such the location of furniture in the room and reduced the amount of perceived light from the surrounding windows. Across trials, there were 3 possible start points for each of the two triangular walkways (6 in total), with two possible directions for each start point (clockwise or counter-clockwise). The order of the start points, and the initial direction taken, was randomized across trials for each participant. These 6 start-points and associated directions were replicated across both the full-vision and reduced-vision conditions for each participant to allow for accurate comparison of performance across visual conditions.

### 2.4. Procedure

Prior to testing, the participant was first fitted with the wireless sensors. They were then instructed that their task was to walk along a (invisible) triangular pathway and to return to the starting point of the pathway as accurately as possible. They were informed that they would be guided along the first two sides of this pathway but that they had to return to the start point unguided. If the participant wore glasses, they were asked to remove these in the reduced vision condition only.

In each trial, the experimenter guided the participant to the start point (point of origin), and advised the participant that this was the point to which they were required to return at the end of the trial. Participants were not explicitly instructed about the speed in which they were required to walk. The experimenter guided the participant along the first two sides of the triangular pathway by loosely holding the participants arm while walking at a pace set by the participant. Participants walked unguided along the third side of the triangle pathway back to the point of origin (see Fig. 2). The experimenter also held the participants' arm whilst they returned to the start point but did not guide the participant in any way. This was done to reassure participants in the reduced-vision condition and to ensure uniformity across conditions. When the participant returned to their perceived location of the start point, they were requested to stop and remain in that location until the experimenter had measured the X, Y coordinates of their location in the room. No feedback was provided during the experiment. The experiment took approximately 30 min for each participant to complete.

### 2.5. Data Analysis

Dependent variables were distance error in metres, orientation angle error in degrees, and gait parameters which included stride length (m), stride time (s), stride velocity (m/s) and turn time (s). Distance error, $E_\mathrm{d}$, was calculated as the square root of the sum of squared 'X' and 'Y' errors between the participant's return point and the point of origin (see Fig. 2(a)).

$$\left[E_\mathrm{d} = \sqrt{(\mathrm{X_F} - \mathrm{X_S})^2 + (\mathrm{Y_F} - \mathrm{Y_S})^2}\right]. \tag{1}$$

The error in the turning angle (Angle error) at turn 2, $E_\mathrm{a}$, was calculated using the reference length of side 3 (3 m), the measured length of side 3 ($L_3$), and the distance error. Using this data, the cosine rule was implemented (see Fig. 2a):

$$\left[E_a = \cos^{-1}\left(\left(9 + L_3^2 - E_\mathrm{d}^2\right)/(6 \times L_3)\right)\right]. \tag{2}$$

A procedure previously reported by Ferraris *et al.* (1995) was used to calibrate the gyroscope data and to derive the acceleration vectors with respect to the sensor unit coordinate axis. Data were then low pass filtered with zero-phase

8th order Butterworth filter with a 50.2 Hz corner frequency. A sample of processed gyroscope data from each sensor location is presented in Fig. 2(b). All heel-strike, toe-off and mid-swing points were identified using the adaptive threshold-based method described by Greene *et al.* (2010). Heel-strike and toe-off points correspond to the initial and terminal contact points during a gait cycle. Mid-swing amplitude was defined as the peak amplitude of the signal during each gait cycle and corresponds to the fastest movement of the shank during a gait cycle. Stride time was defined as the time between subsequent heel-strikes, whereas stride length was defined as the distance travelled during this time and stride velocity was defined as the ratio of stride length to stride time.

Stride length and stride velocity were normalised with respect to the participants height calculated using a previously reported method (Doheny *et al.*, 2010). For each trial, the angular velocity signal was automatically segmented into three walking sections and two turning sections. To detect turns, the mid-swing amplitude was examined. If a given mid-swing amplitude was more than one standard deviation below the mean mid-swing amplitude of data from the total task, it was considered part of the previous turn. The turning phases were then defined as the sections of the signal, starting at the last heel strike before the first mid-swing in each turn and ending at the first toe off after the last mid-swing in the turn. If no mid-swing points were found to occur during a turn, the two longest stance times (the time between a heel-strike and toe-off) were taken to correspond to the turns. The mean and coefficient of variation (CV) were derived for stride length, stride velocity, and stride time.

## 3. Results

Each participant completed 6 trials per visual condition resulting in 12 trials in total. Within the final 468 trials (39 participants $\times$ 12 trials each), we tested for outliers in the distance and angle error data by first calculating the interquartile ranges [$Q1 - 1.5 * IQR$, $Q3 + 1.5 * IQR$] for each group per condition. Performance measures which were greater or lower than this range were subsequently removed from further analyses. This resulted in 25 trials (i.e. 5.34% of the total trials) being removed from the distance error data, and 27 trials (i.e. 7.69% of the total trials) removed from the angle error data (which included the same 25 trials as the distance error data). Of these removed trials, 9 were associated with trials in which participants headed in the opposite direction to the point of return. This occurred once only for 5 different participants in the healthy adult group and 4 participants in the fall-prone group (see Note 2).

Each of the X, Y coordinates for the return points across trials was normalised to the same X, Y coordinate frame (i.e. with a common 0,0 origin, and aligned X and Y axes). The mean X, Y coordinates of each participant's finishing point relative to the point of origin (0,0), for each of the visual conditions, is shown in Fig. 3. We first conducted a Friedman ANOVA to assess whether there was a consistent bias in the direction (left or right along the X axis) or the extent (positive or negative on the Y axis reflecting an over-shoot or under-shoot of the point of origin) of the distance error by comparing performance across the four quadrants demarcated by these axes. Separate ANOVAs were conducted on the performance made by each participant across groups (fall-prone or healthy older adult), in each visual condition (full vision, reduced vision). On the basis of these analyses, no significant distance or left/right direction bias was found for fallers in either the full vision condition [$X^2(3) = 3.48$, $p = 0.32$] or the reduced vision condition [$X^2(3) = 1.32$, $p = 0.72$]. Similarly, there was no evidence of a bias in the healthy older group in their location of the return point in the full vision condition [$X^2(3) = 1.13$, $p = 0.77$]. However, a significant bias was found for the healthy adult group when vision was reduced [$X^2(3) = 11.49$, $p = 0.01$]. We conducted *post-hoc* Wilcoxon tests (using a Bonferroni correction of $p < 0.0125$) on this effect but failed to find any significant differences in distance across the four possible locations of the return point (i.e. over-shoot left; over-shoot right; under-shoot left and under-shoot right) relative to the point of origin. These results suggest that the effect of bias in the reduced vision condition may have been weak.

### *3.1. Distance Error*

The mean distance error for each participant was calculated and averaged across the 'full vision' and 'reduced vision' condition for the healthy (0.36 m, SD = 0.11 m; 0.58 m, SD = 0.17 m, respectively) and fall-prone (0.39 m, SD = 0.17 m; 0.77 m, SD = 0.35 m, respectively) older adults (see Fig. 3 for the mean distance errors per participant in each condition). The mean distance error was then subjected to $2 \times 2$ mixed measures ANOVA with group (fall-prone and healthy older adults) and visual condition (full or reduced vision) as factors. A main effect for visual condition was found ($F(1, 37) = 71.79$, $p < 0.0005$) with a larger distance error in the 'reduced vision' than the 'full vision' condition. The effect of group approached significance ($F(1, 37) = 3.67$, $p = 0.06$), with a larger distance error observed for older adults with a history of falls than their healthy counterparts. The interaction between group and visual condition was significant ($F(1, 37) = 4.68$, $p = 0.04$) and is shown in Fig. 4. To provide further clarification, we conducted separate independent sample $t$-tests across groups in each visual condition. We found that the distance error was greater for fall-prone than healthy older adults when vision was reduced ($t(1, 37) = 2.16$, $p = 0.02$). In contrast, when visual information was available, there was no difference in the distance error across groups ($t(1, 37) = 0.89$, $p = 0.19$). Thus fall-prone older adults were less accurate

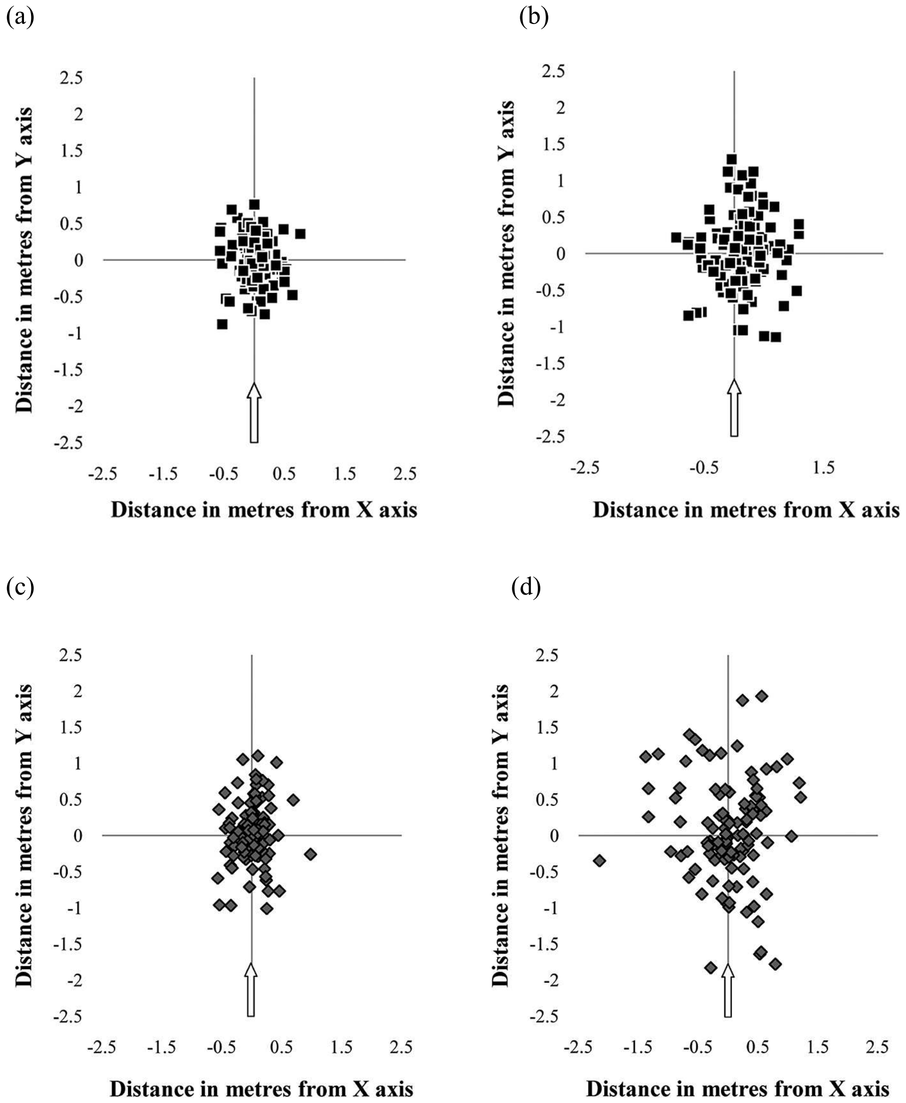


**Figure 3.** Scatterplots representing the return position in each trial for each participant in the healthy (black points) and fall-prone (grey points) older adult groups. The centre point represents the correct return point normalised to the (0, 0) X, Y co-ordinate. The arrows indicate the direction of the participants return trajectory and the location of the return points has been re-aligned according to this direction. The plots are organised as follows: (a) healthy adults' performance in the full vision condition, (b) healthy adults' performance in the reduced vision condition, (c) fall-prone adults' performance in the full vision condition, (d) fall-prone adults' performance in the reduced vision condition.

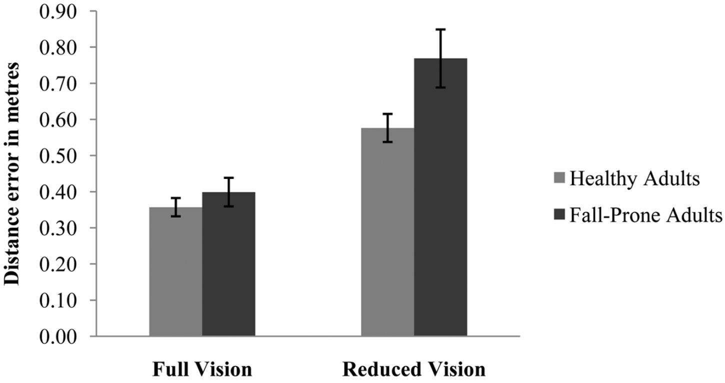


**Figure 4.** A plot of the mean distance error for older adults categorised as 'healthy' (i.e. non-fallers) or 'fallers' across both the full and reduced vision conditions. Error bars represent ±standard error of the mean.

at returning to the point of origin in the triangular completion task relative to healthy older adults, but only when vision was reduced.

### *3.2. Angle Error*

The mean angle error for each participant was measured and averaged across the 'full vision' and 'reduced vision' condition for non-fallers (4.22°, SD = 1.06°; 7.71°, SD = 2.66°, respectively) and fall-prone older adults (4.51°, SD = 1.8°; 10.3°, SD = 6.24°, respectively). The mean results were then subjected to a 2 (fall-prone or healthy older adults) × 2 (full vision or reduced vision) mixed measures ANOVA.

A main effect of visual condition ($F(1, 37) = 45.78$, $p < 0.001$) was found, with larger angle errors made in the 'reduced vision' overall (8.97°, SD = 4.87°) relative to the full vision condition (4.36°, SD = 1.45°). The effect of group failed to reach significance ($F(1, 37) = 2.59$, $p = 0.12$). Although we observed a greater angular error for fallers relative to non-fallers in the reduced vision condition (see Fig. 5), the interaction between vision and group also failed to reach significance ($F(1, 37) = 2.83$, $p = 0.100$).

### *3.3. Stride Length and Stride Length Variance*

Stride length measurements were calculated for each trial and averaged across participants in each of the fall-prone (full-vision 0.94 m, SD = 0.27 m; reduced vision 0.92 m, SD = 0.26 m) and healthy adult groups (full-vision 1.01 m, SD = 0.12 m; reduced vision 0.95 m, SD = 0.12 m) for the two visual conditions.

A 2 × 2 mixed measures ANOVA revealed a main effect of visual condition ($F(1, 37) = 29.48$, $p < 0.0005$), with a shorter stride length in the 'reduced vision' condition relative to the full vision condition. The effect of group (fall-

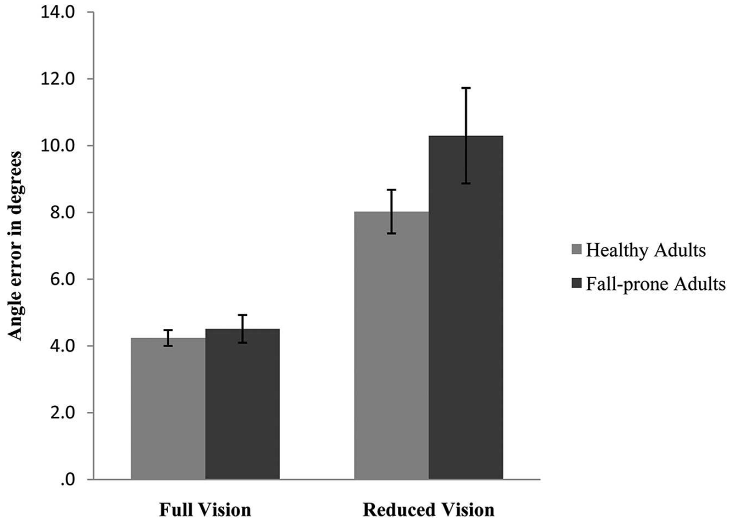


**Figure 5.** A plot of the mean orientation angle error in degrees for older adults categorised 'healthy' (i.e. non-fallers) or 'fallers' across both the full and reduced vision conditions. Error bars represent ±standard error of the mean.

ers and non-fallers) failed to reach significance ($F(1,37) < 1$). An interaction was found between visual condition and group ($F(1,37) = 5.60$, $p = 0.02$), as shown in Fig. 6. To provide further clarification of this interaction, we compared performance across the participant groups using an independent sample, one-tailed $t$-test for each of the visual conditions. We found no significant difference in stride length between the fall-prone and healthy older adults in either the full vision condition ($t(1,37) = 1.06$, $p = 0.15$) or the reduced vision condition ($t(1,37) = 0.55$, $p = 0.29$). However, non-fallers showed greater reduction in stride length as a result of reduced vision compared to fallers.

In a separate analysis, stride length variance measures were subjected to a 2 (group) × 2 (visual condition) mixed ANOVA. There were no effects of visual condition ($F(1,37) < 1$) nor of group ($F(1,37) = 1.00$, $p = 0.32$) found. The interaction between group and visual condition also failed to reach significance ($F(1,37) = 1.43$, $p = 0.24$).

### *3.4. Stride Time and Stride Time Variance*

Stride time was averaged across trials for full and reduced vision conditions for participants grouping the fall-prone (1.99 s, SD = 0.28 s; 2.27 s, SD = 0.46 s, respectively) and healthy groups (2.1 s, SD = 0.45 s; 2.27 s, SD = 0.53 s, respectively).

These data were then subjected to a 2 (group) × 2 (condition) mixed ANOVA. A main effect of visual condition ($F(1,37) = 14.01$, $p = 0.001$) was found, with a slower stride time found in the reduced vision relative

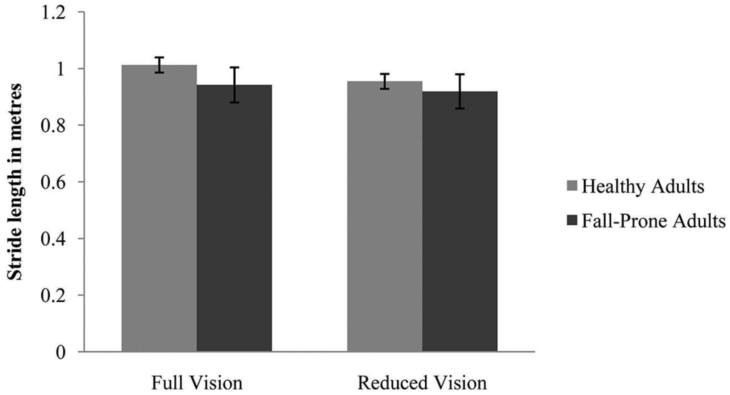


**Figure 6.** A plot of the mean stride length for older adults categorised as 'healthy' (i.e. non-fallers) or 'fallers' across both the full vision and reduced vision conditions. Error bars represent ±standard error of the mean.

to the full vision condition. The effect of group did not reach significance ($F(1,37) < 1$) and there was no interaction between visual condition and group ($F(1,37) < 1$).

Stride time variance data were also subjected to a 2 (group) × 2 (condition) ANOVA. A main effect was found for visual condition ($F(1,37) = 13.85$, $p = 0.001$) with an increase in stride time variance in the 'reduced vision' relative to the full vision condition. No effect of group was found ($F(1,37) < 1$), and there was no interaction between group and visual condition ($F(1,37) < 1$).

### 3.5. *Stride Velocity and Stride Velocity Variance*

The mean stride velocity for each participant in both groups was calculated across visual conditions (see Fig. 7). The healthy older adults group had a mean stride velocity of 0.60 m/s, (SD = 0.13 m/s) and 0.67 m/s, (SD = 0.14 m/s) for the full-vision and reduced vision conditions. The fall prone group had an average of 0.60 m/s, (SD = 0.2 m/s) and 0.63 m/s, (SD = 0.21 m/s) across these respective visual conditions. The data were subjected to a 2 (group) × 2 (condition) mixed ANOVA. A main effect of visual condition ($F(1,37) = 27.68$, $p < 0.0005$) was found, with decreased stride velocity in the reduced vision condition (0.6 m/s, SD = 0.16 m/s) relative to the full vision condition (0.65 m/s, SD = 0.17 m/s). The effect of group failed to reach significance ($F(1,37) < 1$). The interaction effect between groups across conditions failed to reach significance ($F(1,37) = 3.20$, $p = 0.08$). As this interaction was pertinent to our predictions, we conducted an independent sample $t$-test across groups in both visual conditions. We conducted separate independent, one-tailed $t$-tests and found no difference between groups in the reduced vision condition ($t(1,37) = 0.102$, $p = 0.46$) or in the full vision condition ($t(1,37) = 0.71$, $p = 0.24$).

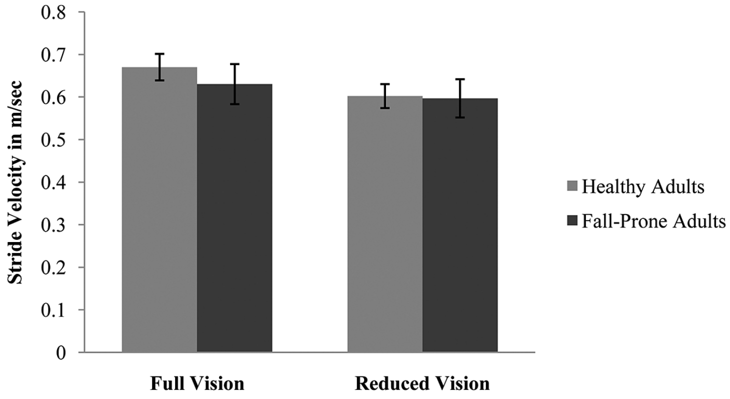


**Figure 7.** A plot of the mean stride velocity for older adults categorised as 'healthy' (i.e. non-fallers) or 'fallers' across the full vision and reduced vision conditions. Error bars represent ±standard error of the mean.

Stride velocity variance data were also subjected to a 2 (group) × 2 (visual condition) mixed ANOVA. There were no effects of visual condition ($F(1, 37) = 1.20$, $p = 0.28$) or group ($F(1, 37) < 1$) and no interaction between group and condition ($F(1, 37) < 1$). Therefore, stride velocity variance was similar for both groups and was not affected by a reduction in visuo-spatial information.

## 4. Discussion

In the present study, older adults with a history of recurrent falls were compared to age-matched controls in their ability to update their spatial location during the active navigation of a relatively large-scale environment. Specifically, we used the triangle completion task, adapted from previous studies investigating path integration (e.g. Klatzky *et al.* 1990; Loomis *et al.*, 1993; Worchel and Mauney, 1951), to assess how efficient older adults were at updating their spatial position during locomotion. In order to assess the role of visual information in this task, we manipulated the amount of visuo-spatial information available. In the 'full-vision' condition, participants could clearly view their surroundings and external cues, such as landmark objects, from all directions for estimating the point of origin on the triangular route. In the 'reduced-vision' condition, participants were required to wear translucent goggles which obscured these visuo-spatial cues, although some lightness perception was maintained (i.e. the position of the windows could be viewed from some directions). We assumed that in the 'reduced vision' condition, the reduction in the reliability of visuo-spatial information would encourage the recruitment of other sensory (interoceptive) information in order to return to the point of origin in the route (e.g. Tcheang *et al.*, 2011).

When visual information was available, we found that older adults with a history of falling performed similarly to healthy older adults with both groups returning to a point which was approximately 40 cm away from the point of origin. This represented an error of approximately 10% of the required distance. When vision was reduced, the error across both groups was approximately 60 cm, representing 20% of the required distance. A distance error of 20% in the reduced vision condition in an older adult group has been previously reported (Adamo *et al.*, 2012). However, performance in estimating the distance of the point of origin on the unguided walk was worse for the fall-prone older adult group than for their healthy counterparts. This result suggests that older adults with a history of falling may have impaired spatial updating for the purpose of path integration when visual input is ambiguous. As both groups had comparable visual, vestibular and proprioceptive functioning (see Table 1), the disparity in spatial updating between groups was not due to pronounced sensory decline in fall prone older adults. In turn, our findings suggest that older persons with a history of falls may have an over-reliance on visual information for efficient spatial updating and are unable to reweight sensory inputs when visual information is uncertain. Furthermore, the results may indicate that older adults with a history of falls require vision to help integrate information from other modalities for the purpose of updating this information during locomotion.

The analysis of gait data indicated that fall-prone older adults did not reduce their stride length or stride velocity to the same extent as healthy older adults when vision was reduced, although this was not statistically significant. Older adults without a history of falling reduced their stride length by 5.7% and stride speed by 10.1% in the reduced vision condition whereas fall-prone older adults reduced their stride length by 2.4%, and stride speed by 5.3%. This may suggest that fall-prone adults do not adjust their gait appropriately relative to healthy older adults when environmental conditions are altered. However, it is worth noting that the fall-prone adults had lower stride velocity overall and shorter stride length than their healthy counterparts, albeit this difference was not statistically significant.

Previous studies have reported that the postural stability of older adults is compromised relative to younger adults when sensory cues are manipulated (Haibach *et al.*, 2009; O'Connor *et al.*, 2008; Speers *et al.*, 2002). Furthermore, others have reported a deficit in older adults' ability to compensate for reductions or alterations to visual input during walking tasks (Chou *et al.*, 2009; Newell *et al.*, 2011). However, in a recent study in which age effects on performance in a path integration task were investigated, Adamo *et al.* (2012) reported no age effects on distance errors across young and older adults when navigating whilst blindfolded through either a real or virtual environment. However, when further sources of sensory information were reduced (e.g. participants were moved in a wheelchair) then age differences emerged with relatively poorer performance in the older adult group, particularly on orientation angles, in both the real and virtual environments.

In the current study, the performance of both fall-prone and healthy older groups on the triangle completion task was affected by reducing visual information. However, this was particularly pronounced in older adults with a history of recurrent falls. This result replicates the previous findings reported by Newell *et al.* (2011), in which fall-prone older adults were relatively worse at estimating the distance to the point of origin in a triangular completion task, but extend those findings in an important way. In particular, the unguided walk in the Newell *et al.* (2011) study was conducted on a 'Gaitrite' mat containing sensors which may have acted as an important visual and proprioceptive cue in guiding the participant's walk within the confines of the mat (although the start point was not indicated on this mat, and its position was randomised across trials). Moreover, as the triangular route was invisible to the participants in the current study, and there were no proprioceptive changes underfoot along the path, this study may represent a more ecologically valid way to assess navigational abilities: as routes are often not marked out, or made explicit, in natural surroundings, navigation relies instead on a mental representation or cognitive map (O'Keefe and Nadel, 1978; Wolbers and Hegarty, 2010).

Although angle error did not differ between groups across visual conditions, previous studies have suggested that estimating the turning angle and distance of a point of origin in triangle completion tasks are distinct but related processes (Allen *et al.*, 2004; Loomis *et al.*, 1999). For example, in studies investigating distance length and turning angle estimation in participants with vestibular deficits, it is reported that the estimation of distance length remains intact while estimation of turning angle is compromised (Glasauer *et al.*, 2002; Takei *et al.*, 1996). Thus different spatial information may be used when estimating either distance length or turning angle during locomotion, with vestibular information playing a dominant role in turning but visual information more dominant for estimating distance. In the current study, a history of recurrent falls was related to a pronounced deficit in estimating the distance to a point of origin, but not for turning angle. To our knowledge, previous studies have not assessed distance and turning angle estimations separately in older adults with a history of recurrent falling. The results of the current study provide a novel insight in to how fall-prone older adults compare to age-matched healthy adults in estimating distance and turning angle during navigation. Nevertheless, future studies in which either the visual or vestibular information was independently manipulated would help to elucidate whether fall prone older adults have a particular reliance on vision for spatial updating, or are unable to reweight sensory input to alternative sensory systems when a dominant sensory source becomes unreliable.

In contrast to studies of gait parameters and associated falls risk in older adults (Maki, 1997; Verghese *et al.*, 2009), variability in stride length and stride velocity did not differ between fallers and non fallers in either of the visual conditions. Possible reasons for this may be due to the relatively short distance of the unguided walk (i.e. a maximum of 3 m in length) during which measurement of stride parameters were taken, or to the availability of landmark objects which may have facilitated navigation. First, as the participant took a few steps to turn into the third side of the triangular path, the total distance over which to measure gait variables was relatively short. This meant that gait measures were based on three to four strides overall which may not have yielded enough data to observe potential differences in stride length variability across groups. In contrast, previous studies typically used a longer walk distance to acquire gait data (e.g. a 4.57 m sensor mat was utilized in Verghese *et al.*'s (2009) study and participants walked approximately 1 m before stepping on to the mat). However, in both the Maki (1997) and Verghese *et al.* (2009) studies, the route was confined to a walkway in a single direction. Second, participants may have made use of object landmarks to facilitate navigation (see Chan *et al.*, 2012). The presence of object landmarks, including the possible role of landmarks in the reduced vision condition such as the light from the windows, may have facilitated navigation. However, information from these landmarks, if used during the task, was not sufficient to provide accurate distance estimates in either group in the full-vision condition, or in the fall-prone group particularly in the reduced vision condition. Our data suggest that future studies on spatial updating should incorporate more explicit manipulation of the nature of the multisensory information available from the environment in order to provide a better assessment of variability in gait parameters between older adults and fall prone older adults.

In the current study, we found that older adults with a history of recurrent falling relative to an age-matched cohort were more impaired in their ability to integrate spatial information for the purpose of path integration when visual input was ambiguous. In addition, fall prone older adults did not adjust their stride length or stride velocity in accordance with the spatial distance error made. Our findings suggest a relative inability to correctly compensate for reduced visual information in fall prone older adults in estimating distance and that this may, in turn, lead to inefficient spatial updating during navigation. This relative inability to compensate for changes in visual information may place older adults at an increased risk of falls in situations where visual information is unreliable, such as dimly lit rooms, or at night, when their surroundings are not highly visible. Moreover, our study goes some way towards providing evidence of an association between deficits in perceptual processes, in this case spatial perception or sensory updating, and a risk of falling. Longitudinal research will help elucidate the aetiology of falls and, in particular, elucidate any causative links between a decline in perceptual processes and incidents of falls. Nevertheless, the present results suggest that when visual input is unreliable older adults with a history of falling do not alter their gait patterns accordingly in order to optimise distance estimation, and these findings have implications not only on our understanding of how multisensory spatial perception is affected by age, but may also suggest interventions for rehabilitating efficient posture and balance control during locomotion in this cohort.

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## Notes

1. Population based norms for assessment measures included the following: a MMSE score of $>25$ for older adults (Crum *et al.*, 1993); a grip strength range (for males and females age 60+) between 10–72 kg for right and left hands (Desrosiers *et al.*, 1995); completing the TUG within 8 (7.0–9.0) s for 60–69 year olds, 9.0 (8.0–10.0) s for 70–79 years, and 11.3 (10.0–12.7) s for 80–99 years (Bohannon, 2006); a BERG balance score of 41–56 is low-, 21–40 is medium- and 0–20 is high-falls risk; LogMAR of 0.0 equates to 20/20 vision (participants in our sample were required to have a LogMAR score of between 0.0 and 0.2); a contrast sensitivity score of 1.68 to 1.90 for the Pelli-Robson Chart across two distances using one or both eyes for adults aged 60+ (Mäntyjärvi and Laitinen, 2001); MFES score of 0 indicates no confidence in completing daily activities without falling, or 10 which indicates no fear of falling.

2. These 9 trials, in which participants walked in the wrong direction, were not removed from the gait parameter analysis as participants were allowed to complete the trial even if they headed in the wrong direction when returning to the point of origin. The direction of the walk would not impact on gait parameters such as stride velocity, stride time and stride length.

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