Title: Gaze behavior of older adults during rapid balance-recovery reactions

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Running head: Gaze during balance reactions
ABSTRACT

Background: Rapid stepping reactions are a prevalent response to sudden loss of balance and play a crucial role in preventing falls. A previous study indicated that young adults are able to guide these stepping reactions amid challenging environmental constraints using ‘stored’ visuospatial information. This study addressed whether healthy older adults also use ‘stored’ visuospatial information in this manner, or are more dependent on ‘online’ visual control.

Methods: Gaze behavior was recorded during rapid forward stepping reactions evoked by unpredictable platform perturbation, as subjects performed a concurrent task demanding visual attention. Challenging obstacles and/or step targets were used to increase demands for accurate foot motion. Twelve healthy older adults (61-73yrs) were compared to 12 young adults (22-29yrs) tested in a previous study.

Results: Similar to young adults, older subjects seldom redirected gaze downward in response to the perturbation (11% of trials), yet were commonly able to clear the obstacle (74% of trials) or land on the target (41% of trials) while stepping to recover balance. The threat posed by the obstacle apparently prompted older adults to initiate early downward saccades during a small proportion (18%) of obstacle trials; however, this did not improve ability to clear the obstacle.

Conclusion: Aging did not alter the predominant visual-control strategy used to guide the stepping reactions. Both young and older persons typically used ‘stored’ visuospatial information, thereby allowing vision/attention to be switched to other demands during the stepping reaction and minimizing head/eye movements that could exacerbate the destabilizing effect of the balance perturbation.

KEYWORDS: aging, balance, environmental constraints, eye movements, postural control, saccades, stepping, triggered reactions, vision, visual attention
INTRODUCTION

Rapid triggered stepping reactions are a prevalent response to sudden loss of balance and play a crucial role in preventing falls (1). Although numerous studies have demonstrated that these compensatory stepping responses are impaired in older adults (2-10), these studies may well underestimate the challenges that older adults face in executing these reactions in daily life, in particular, the need to modulate the limb movement to accommodate environmental constraints. These previous studies have all provided ample unrestricted space to step, whereas various objects and architectural features common to daily-life environments may restrict the length, direction and trajectory of compensatory stepping movements. The ability to modulate the compensatory stepping response to meet such environmental demands is likely an important factor in determining whether an older adult is able to recover from a sudden loss of balance and avoid falling. While the biomechanical demand of accommodating environmental constraints is a significant challenge in itself, the acquisition of visuospatial information regarding the presence and spatial features of these constraints is a fundamental prerequisite for modulating the foot trajectory and may well pose additional difficulties for older adults.

The gaze behavior used to acquire visuospatial information about environmental constraints on foot movement during gait and volitional stepping has been studied extensively (11-15); however, in these situations, the step direction is known in advance and visual sampling can be directed, in a predictive manner, to the intended path of gait progression and/or landing site for the forthcoming step (11, 12). Furthermore, the step can be delayed or slowed to allow more time for visual scanning of the surroundings and for planning of the foot movement. Conversely, a stepping reaction to a sudden unexpected balance perturbation must be executed very quickly in order to safeguard postural stability, and cannot be planned in advance, as the
step length and direction are dictated by the need to arrest the falling motion, which is defined by the characteristics of the perturbation (1).

A recent study indicated that young adults are commonly able to guide perturbation-evoked stepping reactions using ‘stored’ visuospatial information acquired prior to perturbation onset, even when objects placed severe constraints on foot trajectory (16). It is not clear, however, whether older persons are equally able to use ‘stored’ information in this manner. For example, older persons may be less likely to direct attention to their surroundings (particularly when engaged in a distracting task) due to deficits in visual attention (17) or may be less able to accurately store and retrieve salient visuospatial information due to declines in working spatial memory (18). Such factors could force a greater reliance on ‘online’ visual fixation of the foot and/or floor to guide the stepping movement.

To determine the visual control strategy used by older adults, we examined their gaze behavior during forward-directed stepping reactions evoked by sudden unpredictable postural perturbation. Challenging obstacles and/or step targets were used to increase demands for accurate foot movement, and subjects performed a concurrent visuomotor distraction task that required them to direct gaze straight ahead. Downward gaze shifts during the response to the perturbation were inferred to indicate possible use of ‘online’ visual control, whereas the absence of such gaze shifts implies reliance on previously ‘stored’ visuospatial information. To explore age-related differences, the present results were compared to previously published data from younger adults (19). The intent of these initial studies was to understand the visual control strategies used in familiar environments; hence, subjects were allowed to view their surroundings prior to the start of each trial. Ongoing work is examining how these strategies change when the environment is unfamiliar or changes in an unpredictable manner.
METHODS

Twelve naïve community-dwelling older adults (OA) (3/9 male/female; ages 61-73, height 145-182cm, mass 50-101kg) were tested and compared to twelve younger adults (YA) tested in a previous study (5/7 male/female; ages 22–29, height 160–181cm, mass 54–93kg) (19). All subjects were right-hand and right-leg dominant, and were able to stand and walk without aid. Exclusion criteria included diabetes, neurological or sensory disorders, recurrent dizziness or unsteadiness, use of medications that may affect balance, joint replacement, medical conditions interfering significantly with daily activities, or functional limitations of limb use. Subjects were required to have a minimum uncorrected Snellen visual acuity of 20/40 and were not permitted to wear corrective lenses during the experiment (to avoid potential interference with eye-movement measurements). Each subject provided written informed consent to comply with ethics approval granted by the institutional review board.

The protocol was essentially the same as in the earlier study involving young adults (19). Compensatory stepping reactions were evoked by sudden, unpredictable horizontal movements of a large (2m×2m), computer-controlled, moveable platform (20). Subjects began all trials in a standardized comfortable foot position (21) at the center of the platform (Figure 1). A safety harness was worn, and safety guardrails and walls were mounted around the platform perimeter. To deter downward gaze shifts during the interval prior to perturbation onset, they performed a visuomotor “thumb tracking” task (22-25) that required gaze to be directed straight ahead, and the platform perturbation was delivered at an unpredictable time during the 20s duration of this task. The task involved pursuit tracking of pseudorandom target motion displayed on a computer screen, using the right thumb to rotate a potentiometer controlling the pursuit cursor (Figure 1). Vigilance was encouraged by a monetary reward for accurate tracking.
Blocks of trials were performed for four environmental-constraint conditions: (1) no-constraint, (2) obstacle-only, (3) target-only, and (4) obstacle-plus-target (see Figure 1). The focus was on forward stepping reactions evoked by large backward platform translations (acceleration $3.0\text{m/s}^2$, velocity $0.9\text{m/s}$, duration $0.6\text{s}$). Each trial block included (in random order) three such perturbation trials plus five “wildcard” perturbation trials included solely to increase unpredictability (direction forward, backward, left or right; acceleration $0.13–3.0\text{m/s}^2$; velocity $0.2–0.9\text{m/s}$). An additional large-backward-translation trial was performed at the very start of the session. The full protocol comprised two blocks of randomized trials for each constraint condition, the order counterbalanced both within and across subjects. To avoid fatigue, three older adults performed a shortened version of the protocol. Table 1 provides details of the protocol and the numbers of trials performed.

Subjects were told to do whatever came naturally to prevent falling, but invariably stepped in the large-perturbation trials. At the start of each trial block, the subjects’ attention was directed to the constraint condition. They were told that if they needed to step in order to recover balance, they should avoid contacting the obstacle and/or direct the step so as to land the great toe on the target. To motivate the subjects, they were told that failure to avoid obstacle contact or to land on the target during forward steps would result in a penalty that would reduce their chances of winning the monetary reward for accurate tracking, but there was no incentive given to either encourage or discourage step initiation. The subject was free to look at the floor during the interval between trials (~30s); however, once the trial started, it was not possible to see the obstacle or step targets (in central or peripheral fields) without redirecting gaze downward, away from the tracking-task display.

A lightweight, video-based eye tracker (ASL model 501) was worn on the head and used to record movements of the left eye (sampling rate 60 Hz). This system uses infrared corneal
reflections to determine gaze direction, relative to the head, and superimposes the gaze location on video images recorded by a forward-facing “scene camera” mounted rigidly on the head. These images were used to determine whether the subject looked downward following perturbation onset, as well as the onset time of each such gaze shift. Two force plates, embedded in the surface of the moveable platform, were sampled at 200Hz to determine time of foot-off and foot-contact. Video-recordings from four overhead cameras were used to determine “obstacle success” (stepping over the obstacle without contacting it) and “target success” (landing the great-toe on the target line), and to measure step-to-target accuracy (by resolving, to within 1cm, the position of a reflective marker on the great toe relative to a grid marked on the platform surface). All timing values were defined relative to onset of platform acceleration (0.1m/s\(^2\)) recorded by an accelerometer. Only gaze shifts that occurred after perturbation onset and prior to foot contact were considered.

A two-way analysis of variance (ANOVA) was performed to assess the effect of constraint condition and age group on percentage of trials in which downward gaze shift occurred during the evoked forward-step reactions. The data set comprised four percentage scores per subject (one score for each of the four constraint conditions). To avoid violation of the assumptions underlying the ANOVA, the data were rank-transformed prior to analysis (this procedure is equivalent to performing a non-parametric test (26)). Exclusion of trials with technical/methodological problems (e.g. malfunction of the eye-tracker, misunderstanding of instructions), left 256 of 264 trials available for analysis for the older adults and 280 of 300 trials for the young adults.
RESULTS

Subjects in both age groups redirected gaze downward following perturbation onset in only a small proportion of trials [11% (27/256) in OA, 17% (47/280) in YA]. Although there was no main effect due to aging [F(1,22)=1.67; p=0.21], there was a significant age-constraint interaction [F(3,66)=3.77; p=0.01]. Older adults looked down most often when the obstacle was present [17% (11/63) of obstacle-only trials; 19% (12/64) of obstacle-plus-target trials] and almost never looked down when there was no obstacle [6% (4/66) of target-only trials; 0% (0/63) of no-constraint trials]. In contrast, young adults looked down most often when the step target was present [24% (16/68) of target-only trials; 37% (27/73) of obstacle-plus-target trials], and almost never looked down when there was no step target [4% (3/70) of obstacle-only trials; 1% (1/69) of no-constraint trials]. See Figure 2.

Statistical analysis of the gaze-shift timing was precluded by the small number of trials in which gaze shift occurred; however, there does appear to be a trend for faster onset of downward gaze shift in the older adults (mean±SD: 307±127ms, versus 391±157ms in young adults). This is likely due to the trend for older adults’ saccades to be temporally linked to the obstacle crossing, which occurred at an early stage of the step, whereas the young adults’ saccades were more closely linked to target strike, which occurred at the completion of the step. Thus, in obstacle-plus-target trials, the interval between onset of gaze shift and onset of obstacle crossing was 207±211ms in the older adults, whereas the onset of gaze shift in the young adults preceded target strike by a comparable time margin (271±149ms). See Figure 3. These apparent age-related differences in saccade timing occurred in the absence of any age-related differences in step timing, either for foot-off [233±46ms in OA, 209±49ms in YA; F(1,22)=1.23, p=0.28] or foot-contact [626±137ms in OA, 651±151ms in YA; F(1,22)=1.37, p=0.25].
The tendency of older adults to look down most frequently when the obstacle was present could be related to difficulty in performing the task. Although the older subjects were able to clear the obstacle in the majority of trials, their success rate was significantly lower than that of the young adults [74% (94/127) versus 97% (139/143) of obstacle trials; F(1,22)=5.77; p=0.03]. However, the tendency of older adults to direct gaze downward during some obstacle trials did not appear to improve ability to clear the obstacle. When looking downward, older adults had a success rate of 70% (16/23), compared to a rate of 75% (78/104) when not looking down.

The older adults were also less proficient than the young adults in stepping to the target [success rate: 41% (53/130) vs. 58% (82/141) of target trials; F(1,22)=5.89; p=0.02], but downward gaze shift did not appear to improve their ability to land on the step target. In those few step-target trials where older adults did look down, their success rate in stepping to the target was only 25% (4/16), compared to 43% (49/114) when they did not look down. The magnitude of the mean step-to-target error (medio-lateral distance from great toe to target tape) was also slightly worse when redirecting gaze downward (49±49mm versus 56±64mm). In contrast, the accuracy of the young adults did appear to benefit from looking downward. The step-to-target success rate improved from 50% (49/98) to 77% (33/43) and mean step-to-target error improved by 2cm (21±20mm versus 41±39mm) in trials where downward gaze-shift occurred.

**DISCUSSION**

Older adults typically did not require ‘online’ visual fixation of the foot or floor to guide stepping reactions evoked by large unpredictable perturbations, even when challenging environmental constraints on the foot trajectory were imposed. As with younger adults, it instead appears that compensatory stepping responses were guided using ‘stored’ visuospatial information about the surrounding environment obtained prior to the perturbation. The older
adults were able to successfully direct the foot over a challenging obstacle in about 75% of trials and landed the foot on a narrow target in nearly 50% of trials, despite the fact that the perturbation evoked downward gaze shift in only 14% of trials involving obstacles and/or targets. Furthermore, there was no improvement in constraint performance in those trials where gaze was redirected downward during the response. Successful guidance of the step in trials where there was no downward gaze shift cannot be attributed to use of peripheral vision, since the geometry of the setup made it impossible to view the constraints in any portion of the visual field when gaze was directed straight ahead at the thumb-tracking monitor. The absence of ‘online’ visual feedback implies that subjects must have relied on previously ‘stored’ visuospatial information.

The present findings are consistent with the proposition that an internal ‘spatial map’ of the surroundings, formed prior to perturbation onset, was combined with multisensory feedback about the perturbation-induced body motion in order to modulate the step trajectory (19, 27), and do not support speculation that older adults might instead be more dependent on ‘online’ visual control. Reliance on a preformed spatial map, rather than ‘online’ visual feedback, allows the stepping reaction to be initiated very rapidly after perturbation onset (avoiding potential delays that would occur if it were necessary to perform a visual scan of the floor) and frees vision and attention to be directed to other task demands. Furthermore, by avoiding the need for head or eye movement after perturbation onset, this control strategy has a number of advantages that may be particularly important in helping older adults recover equilibrium: 1) it avoids instability that can be induced by eye and head movements (28); 2) it allows the head to serve as a stable “sensory platform” that optimizes visual and vestibular feedback (29-32); 3) it promotes acquisition of self-motion information via visual optic-flow cues (33); and 4) it reduces the need
to update ‘stored’ spatial information as a consequence of changes in gaze- or head-centered reference frames (34, 35).

In the small number of trials where gaze was directed downward, the saccade onset times were actually faster in the older subjects than in the young; however, this finding must be interpreted carefully. In contrast to previous studies showing age-related slowing of saccades (36, 37), the present study included no explicit instructions to redirect gaze as quickly as possible. The more rapid responses that we observed in the older subjects were likely due to differing task priorities. In particular, a greater concern for clearing the obstacle, in some of the older adults, may have prompted more rapid visual redirection, at an early stage of the step, whereas the gaze shifts in the younger subjects appeared to be more strongly associated with landing the foot on the target at the completion of the step.

The fact that gaze redirection toward the foot and obstacle did not improve the ability of older adults to clear the obstacle raises the possibility that performance might have improved, in some trials, had the saccade been initiated earlier and thereby allowed additional time for visuospatial processing. Recent studies of volitional stepping have, in fact, shown that older adults do fixate forthcoming step locations sooner (and longer) than younger persons when given the opportunity (14, 15). There is certainly no doubt that both age groups have the potential for more rapid saccade initiation. In comparison to the mean latencies of ~300-400ms that we observed, saccadic reaction-time studies have reported mean latencies as fast as 194 ms and 231ms in healthy young and older adults, respectively (38), and it appears that these reaction times can be even faster (by ~70ms) when there is a simultaneous postural perturbation (39).

The conclusions of the present study are applicable to the control of balance in familiar environments, as subjects were allowed to view their surroundings prior to the start of each trial (and these surroundings remained the same during each block of trials) but were not able to
simply “memorize” the required stepping movements. The unpredictable trial-to-trial variation in perturbation direction and magnitude induced varying patterns of body motion that made it impossible to preplan to step in a particular direction or to preplan the specific foot trajectory required to clear the obstacle or land on the target. Instead, it was necessary for the CNS to rapidly integrate visuospatial information about the surroundings with multi-sensory feedback about the body motion induced by the perturbation. Although it is possible that the predictable environment predisposed subjects to rely on ‘stored’ visuospatial information to guide the stepping reactions, the use of such a control strategy is also supported by our most recent studies in which the environment was completely novel and unpredictable (40). Subjects stood amid multiple obstacles that moved intermittently and unpredictably prior to perturbation onset, but were able to avoid the obstacles while stepping to recover balance, even though gaze was never redirected at the obstacles, step foot or landing site in response to the perturbation.

From a fall-prevention perspective, further research is needed to determine whether the ability of older adults to execute effective compensatory steps in “cluttered” environments could be enhanced by training: 1) increased use of ‘online’ visual control (e.g. rapid fixation of potential step landing sites in reaction to postural perturbation), and/or 2) more effective acquisition/storage of visuospatial information prior to loss of balance (e.g. more attentive monitoring of one’s surroundings). Although the present study indicated that healthy older adults were usually successful in using ‘stored’ visuospatial information to guide the stepping movements, their capacity to do so may be challenged when the environment is more complex and less predictable. Work is in progress to address these issues.
ACKNOWLEDGMENTS

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REFERENCES


Table 1 – Details of the experimental protocol

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\(\dagger\) A, B, C and D are used to indicate the order in which the four constraint conditions were tested. For example, in one order pattern: A=no-constraint, B=obstacle-only, C=target-only and D=obstacle-plus-target. Each subject was randomly assigned to one of four different order patterns.

\(\£\) All 12 young adults and 9 of the older adults performed the full protocol. The remaining 3 older adults performed the shortened protocol. The listed trial numbers pertain to trials where subjects performed the visuomotor thumb-tracking task (the 12 young adults and 6 of the older adults also performed no-tracking trials, which were included for purposes unrelated to the present study).

\(\dagger\) These trials, which involved forward steps evoked by large backward platform translation (acceleration 3.0 m/s\(^2\); velocity 0.9 m/s; duration 0.6 s), were the focus of the analysis. The total number of trials available for analysis was 300 for the young adults (12 subjects x 25 trials per subject) and 264 for the older adults (9 subjects x 25 trials + 3 subjects x 13 trials).

\(\£\) The “wildcard” trials were pseudo-random selections of various perturbation directions (forward, backward, left, right) and magnitudes (acceleration 0.13–3.0 m/s\(^2\); velocity 0.2–0.9 m/s) and were included to increase unpredictability (no-perturbation “catch” trials were also included).
FIGURE CAPTIONS

Figure 1: Photographs showing a subject standing in the starting position on the moveable platform. The step targets (A) and obstacle (B) are also shown, corresponding to the target-only and obstacle-only task conditions, respectively. The obstacle was a styrofoam-covered metal bar (diameter 3.5cm; length 150cm; height = 12.5% of body height; distance between obstacle and end of toes = 2.5% of body height); a block of foam rubber (2.4cm thick) filled the gap between the bar and the platform surface to prevent stepping beneath the bar. The target was a line of red tape (2cm×75cm) extending forward in front of each foot, intended to restrict medio-lateral step placement without compromising ability to arrest the forward perturbation-induced body motion. In the unconstrained task condition, the targets and obstacle were both removed. In the obstacle-plus-target condition, the targets and obstacle were both installed. The inset photographs depict the computer monitor display (target and cursor) and the thumb-tracking apparatus used to perform the visuomotor tracking task.

Figure 2: Relative frequency of downward gaze shift for each constraint condition. Each bar represents the percentage of trials in which a downward gaze shift occurred, for young adults (unfilled bars) and older adults (filled bars). Note that gaze shifts were infrequent for all constraint conditions. Older adults tended to look downward most frequently when an obstacle was present, whereas young subjects tended to look downward more often in step-target trials.

Figure 3: Timing of downward gaze shift, for the constraint conditions where gaze shift occurred most commonly, i.e. step-target trials in young adults (unfilled bars) and obstacle trials in older adults (filled bars). Means (and standard deviations) are shown for the onset of the downward gaze shift, in relation to: perturbation onset, start of obstacle clearance (i.e. as indicated by the antero-posterior position of the great toe) and time of step-target strike (i.e. time
of initial foot contact). Positive values for the three sets of timing data indicate that the gaze shift occurred after perturbation onset, prior to obstacle crossing or prior to step-target strike, respectively. Asterisks highlight the similarity in temporal coupling between onset of gaze shift and: 1) obstacle crossing in the older subjects; 2) step-target strike in the young adults.
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