Gaze Behavior of Older Adults During Rapid Balance-Recovery Reactions

John L. Zettel,1,2,3 William E. McIlroy,1,5,6 and Brian E. Maki1,2,3,4,6

1Centre for Studies in Aging, Sunnybrook Health Sciences Centre, Toronto, Canada.
2Institute of Medical Science, 3Institute of Biomaterials and Biomedical Engineering, and
4Department of Surgery, University of Toronto, Canada.
5Department of Kinesiology, University of Waterloo, Canada.
6Toronto Rehabilitation Institute, Canada.

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 participants 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 (61–73 years) were compared to 12 young adults (22–29 years) tested in a previous study.

Results. Similar to young adults, older participants 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.


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 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. Whereas 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 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 place 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 participants performed a concurrent visuo-motor 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, participants 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 male, 9 female; ages 61–73 years, height 145–182 cm, mass 50–101 kg) were tested and compared to 12 younger adults (YA) tested in a previous study (5 male, 7 female; ages 22–29 years, height 160–181 cm, mass 54–93 kg) (19). All participants 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. Participants 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 participant provided written informed consent to comply with ethics approval granted by the institutional review board.

The protocol was essentially the same as that in the earlier study involving YA (19). Compensatory stepping reactions were evoked by sudden, unpredictable horizontal movements of a large (2 m × 2 m), computer-controlled, moveable platform (20). Participants 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 simulate the real-life situation where loss of balance occurs while engaged in an ongoing visual task, participants performed a visuo-motor “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 20-second 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), and vigilance was encouraged by a monetary reward for accurate tracking.

Figure 1. Photographs showing a participant 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 3.5 cm; length 150 cm; height = 12.5% of body height; distance between obstacle and end of toes = 2.5% of body height); a block of foam rubber (2.4 cm 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 (2 cm × 75 cm) extending forward in front of each foot, intended to restrict mediolateral 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. Insets: the computer monitor display (target and cursor) and the thumb-tracking apparatus used to perform the visuo-motor tracking task.
Blocks of trials were performed for four environmental constraint conditions: (a) no-constraint, (b) obstacle-only, (c) target-only, and (d) obstacle-plus-target (see Figure 1). The focus was on forward stepping reactions evoked by large backward platform translations (acceleration 3.0 m/s\(^2\), velocity 0.9 m/s, duration 0.6 s). Each trial block comprised (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 m/s\(^2\); velocity 0.2–0.9 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 participants. 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.

Participants 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 participants’ attention was directed to the constraint condition. They were told that if they needed to step 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 participants, 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. Participants were free to look at the floor during the interval between trials (~30 s); however, after 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 (Model 501; Applied Sciences Laboratories; Bedford MA) 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 participant 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 200 Hz 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 1 cm, 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 (0.1 m/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 participant (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 nonparametric test (26)]. Ties between two or more scores were assigned the average ranks for those scores (e.g., if scores were 10%, 20%, 20%, and 30%, corresponding ranks would be 1, 2.5, 2.5, and 4). Exclusion of trials with technical and/or methodological problems (e.g., malfunction of the eye-tracker, misunderstanding of instructions) left 256 of 264 trials available for analysis for the OA group and 280 of 300 trials for the YA group.

### RESULTS

Participants 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; \( p = .21 \)], there was a significant age-constraint interaction [F(3,66) = 3.77; \( p = .01 \)]. The OA group 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

### Table 1. Details of Experimental Protocol

<table>
<thead>
<tr>
<th>Constraint Condition*</th>
<th>No. of Large Forward-Step Trials</th>
<th>No. of “Wildcard” Trials</th>
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<tbody>
<tr>
<td>Block No.</td>
<td>Full Protocol</td>
<td>Short Protocol</td>
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<tr>
<td>1</td>
<td>A</td>
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<td>8</td>
<td>B</td>
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<tr>
<td>9</td>
<td>A</td>
<td>3</td>
</tr>
<tr>
<td>Total No. of trials</td>
<td>25</td>
<td>13</td>
</tr>
</tbody>
</table>

Notes: *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 participant was randomly assigned to one of four different order patterns.

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 participants × 25 trials per participant) and 264 for the older adults (9 participants × 25 trials + 3 participants × 13 trials).

The “wildcard” trials were pseudorandom selections of various perturbation directions (forward, backward, left, and 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).

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 during which participants 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).
obstacle (6% [4/66] of target-only trials; 0% [0/63] of no-constraint trials). In contrast, the YA group 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 OA group (mean ± standard deviation [SD] = 307 ± 127 ms vs 391 ± 157 ms in the YA group). This result is likely due to the trend for OA’s saccades to be temporally linked to the obstacle crossing, which occurred at an early stage of the step, whereas the YA’s 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 ± 211 ms in the OA group, whereas the onset of gaze shift in the YA group preceded target strike by a comparable time margin (271 ± 149 ms); 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 [392 ± 55 ms in OA, 401 ± 67 ms in YA; F(1,22) = 1.23, p = .28] or foot-contact [626 ± 137 ms in OA, 651 ± 151 ms in YA; F(1,22) = 1.37, p = .25].

The tendency of the OA group to look down most frequently when the obstacle was present could be related to difficulty in performing the task. Although the older participants were able to clear the obstacle in the majority of trials, their success rate was significantly lower than that of the YA group (74% [94/127] vs 97% [139/143] of obstacle trials; F(1,22) = 5.77; p = .03). However, the tendency of the OA group 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 OA participants were also less proficient than the YA participants in stepping to the target [success rate: 41% (53/130) vs 58% (82/141) of target trials; F(1,22) = 5.89; p = .02], but downward gaze shift did not appear to improve their ability to land on the step target. In those few step-target trials during which 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 ± 49 mm vs 56 ± 64 mm). 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 2 cm (21 ± 20 mm vs 41 ± 39 mm) in trials during which downward gaze-shift occurred.

**Discussion**

The OA participants 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 OA group was able to successfully direct the foot over...
have improved, in some trials, had the saccade been initiated we cannot rule out the possibility that performance might appear to improve the ability of older participants to clear the obstacle; however, meaningful statistical analysis was

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 to modulate the step trajectory (19,27); they 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: (a) it avoids instability that can be induced by eye and head movements (28); (b) it allows the head to serve as a stable “sensory platform” that optimizes visual and vestibular feedback (29–32); (c) it promotes acquisition of self-motion information via visual optic-flow cues (33); and (d) 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 during which gaze was directed downward, the saccade onset times were actually faster in the older participants 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 participants were strongly associated with landing the foot on the target at the completion of the step.

Gaze redirection toward the foot and obstacle did not appear to improve the ability of older participants to clear the obstacle; however, meaningful statistical analysis was precluded due to the rarity of gaze-shift trials. Furthermore, we cannot rule out 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 do 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 ~300–400 ms that we observed, saccadic reaction-time studies have reported mean latencies as fast as 194 ms and 231 ms in healthy young and older adults, respectively (38), and it appears that these reaction times can be even faster (by ~70 ms) 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 the participants were given ample opportunity to view their surroundings prior to the start of each trial and these surroundings remained the same during each block of trials. However, participants were not able to simply “memorize” the required stepping movements. The unpredictable trial-to-trial variation in perturbation direction made it impossible to preplan a step in a particular direction. Furthermore, the unpredictable trial-to-trial variation in perturbation magnitude induced widely varying degrees of body motion, which precluded the possibility of preselecting a “generic” step trajectory that could guarantee obstacle clearance and/or landing on the target. There was, in fact, considerable perturbation-dependent modulation of the step. For example, in obstacle trials, mean forward step lengths for small (1 m/s²), medium (2 m/s²), and large (3 m/s²) perturbations were 17%, 25%, and 29% of body height, respectively. In addition, participants did not consistently use the same leg to execute the forward steps [33% of participants exhibited both left- and right-leg responses], and did not execute a forward step in a substantial proportion of trials [36% of small and medium backward-translation trials]. Such variation argues against preplanning of a generic response and instead supports the view that each individual response was modulated in accordance with online sensory feedback about the body motion induced by the perturbation (in combination with stored visuospatial information about the surroundings).

It is possible that the predictable environmental constraints used in this study promoted increased reliance on stored visuospatial information to guide the stepping reactions. The performance of the visuomotor tracking task may have also contributed, by inhibiting downward saccades. However, the use of stored visuospatial information is also supported by our most recent studies in which the environment was completely novel and unpredictable, and gaze behavior was totally unconstrained (40). Participants 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. In support of the ecologic validity of the tracking-task paradigm, we note that the need to direct gaze forward to perform an ongoing cognitive or motor task,
while maintaining balance, is not an uncommon occurrence in daily life.

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: (a) increased use of online visual control (e.g., rapid fixation of potential step landing sites in reaction to postural perturbation), and/or (b) more effective acquisition and/or 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.

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Dr. Zettel is currently with Human Health and Nutritional Sciences, University of Guelph, Guelph, Canada.

CORRESPONDENCE

Address correspondence to Brian E. Maki, PhD, PEng, Centre for Studies in Aging, Sunnybrook Health Sciences Centre, 2075 Bayview Avenue, Toronto, Ontario, Canada M4N 3M5. E-mail: brian.maki@sri.utoronto.ca

REFERENCES


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