

Gaze behavior governing balance recovery in an unfamiliar and complex environment

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Abstract

Visuospatial information regarding obstacles and other environmental constraints on limb movement is essential for the successful planning and execution of stepping movements. Visuospatial control strategies used during gait and volitional stepping have been studied extensively; however, the visuospatial strategies that are used when stepping rapidly to recover balance in response to sudden postural perturbation are not well established. To study this, rapid forward stepping reactions were evoked by unpredictable support-surface acceleration while subjects stood amid multiple obstacles that moved intermittently and unpredictably prior to perturbation onset (PO). To prevent predictive control, subjects performed only one trial (their very first exposure to the perturbation and environment). Visual scanning of the obstacles and surroundings occurred prior to PO in all subjects; however, gaze was never redirected at the obstacles, step foot or landing site in response to the perturbation. Surprisingly, the point of gaze at time of foot-contact was consistently and substantially anterior to the step-landing site. Despite the apparent absence of ‘online’ visual feedback related to the foot movement, the compensatory step avoided obstacle contact in 10 of 12 young adults and 9 of 10 older subjects. The results indicate that the balance-recovery reaction was typically modulated on the basis of visuospatial environmental information that was acquired and continually updated prior to perturbation, as opposed to a strategy based on ‘online’ visual control. The capacity to do this was not adversely affected by aging, despite a tendency for older subjects to look downward less frequently than young adults.

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Visuospatial information regarding obstacles and other environmental constraints on limb movement is essential for the successful execution of stepping movements. During gait and volitional step initiation, the limb movement can be planned and guided using visual constraint information acquired in advance of the step, as well as ‘online’ visual feedback about the limb position and/or step-landing site [4,6,11,25,27]. However, the visuospatial control strategies used when stepping rapidly to recover balance in response to a sudden postural perturbation are not well established. During gait and volitional stepping, the

step direction, distance and trajectory can be planned 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. Furthermore, the step initiation and execution can be delayed or slowed, if necessary, to allow more time for visual scanning of the surroundings and for planning of the foot movement. Conversely, stepping reactions evoked by sudden unpredictable balance perturbation cannot be planned in advance, as the step length and direction are dictated by the need to arrest the perturbation-induced falling motion, but the urgent need to react rapidly may severely limit opportunity to redirect gaze so as to identify a suitable landing site and guide the foot to that site [18].

Recent studies of perturbation-evoked stepping and reaching movements [7,31] have led to speculation that the central nervous system (CNS) guides these movements using an egocentric

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spatial map of the immediate surroundings that is automatically updated on an ongoing basis. This avoids the delay that would occur if instead it were necessary to visually guide the compensatory movement after the onset of the perturbation. If and when a sudden unexpected loss of balance occurs, the pre-formed map can be used (in combination with ‘online’ multisensory feedback about the perturbation-induced body motion) to immediately initiate a very rapid stabilizing limb movement that is directed and scaled so as to accommodate surrounding environmental constraints. However, the previous studies supporting this theory [7,31] have involved repeated trials with predictable and static obstacles or handrails, which may have biased visual sampling and encouraged a strategy of relying on a pre-formed spatial map. To determine whether a pre-formed map is used in the more demanding situations that are typical of daily life, it is necessary to focus on task conditions where the characteristics of the perturbation and environment are unfamiliar. It is also important to examine more complex environments that could potentially overwhelm mapping capacity, particularly in older adults (e.g. due to age-related decline in attention [8], working spatial memory [29] or visuospatial processing [28]).

The present study addressed the situation where the environment is unfamiliar, complex and unpredictable. A rapid stepping reaction was evoked by a sudden postural perturbation deliv-

ered while the subject stood amid an array of multiple obstacles controlled to move intermittently and unpredictably. To prevent learning of predictive control strategies, the perturbation was unpredictable and subjects performed only one trial (very first exposure to the perturbation and environment). We hypothesized that young adults would rely on visuospatial information acquired prior to perturbation onset (PO), and hence would select and execute an appropriate pattern of foot movement (recovering equilibrium without contacting obstacles) without use of ‘online’ visual feedback (i.e. without directing gaze at the obstacles, foot or step-landing site subsequent to PO). It was further hypothesized that older adults would be less successful in avoiding the obstacles, due to a reduced capacity to accurately acquire, process and store the salient visuospatial information or to incorporate this information effectively into the control of the foot trajectory.

Twelve young adults (YA; 6 male, 6 female; ages 22–33 years) and 10 community-dwelling older adults (OA; 5 male, 5 female; ages 60–76 years) were tested. All were right-side dominant (preferred right limbs for writing and kicking), were able to stand and walk without aid, and had a minimum uncorrected Snellen visual acuity of 20/40. Exclusion criteria included neurological or sensory disorders, recurrent dizziness or unsteadiness, use of medications that affect balance, joint

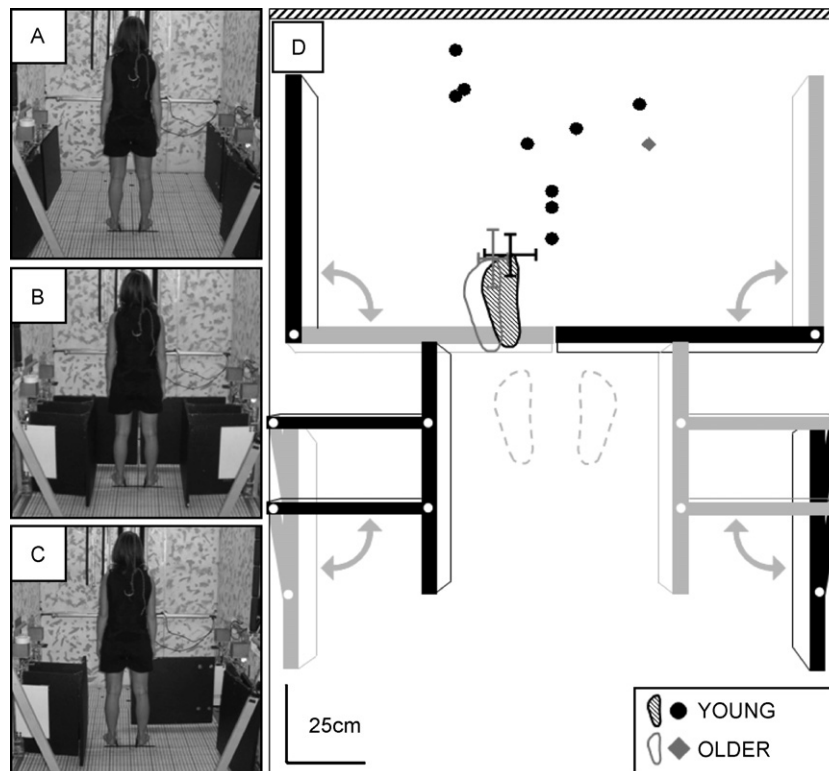


Fig. 1. Photographs of the motion platform showing the range of motion of the four moveable obstacles (all retracted in A; all extended in B), along with the final obstacle configuration prior to perturbation onset (C). Panel D shows the step location and point of gaze at time of foot-contact, superimposed on a schematic drawing (overhead view) of the platform and obstacles. The final obstacle configuration (corresponding to photograph C) is drawn with black lines, arrows and gray lines indicate the range of motion of each obstacle, and the hatched line indicates the location of the front wall. Footprints indicate the average starting foot position (dashed gray outline) and the mean step location (solid black lines and hatched fill for young adults; solid gray lines and no fill for older adults) for the 19 subjects who avoided obstacle contact by stepping forward with the left leg in response to the backward platform motion (10 of 12 young adults, 9 of 10 older adults). The bars superimposed on the two step-location footprints indicate the S.D. for the great-toe landing location. The symbols indicate the point of gaze at time of foot-contact for the 11 subjects (10 young, 1 older) who looked at the floor; the other 8 subjects (all older adults) were looking forward at the walls at time of foot-contact.

replacement, medical conditions interfering with daily activities, or functional limitations of limb use. Subjects provided written informed consent to comply with ethics approval granted by the institutional review board (in accordance with the Declaration of Helsinki).

Perturbations were applied using a large ($2\text{ m} \times 2\text{ m}$), computer-controlled platform that could produce sudden, unpredictable horizontal movements [19]. The platform was semi-enclosed, with walls mounted at the front and at the sides. Subjects stood in a standardized comfortable starting position [22] at the center of the platform, amid four large obstacles ($60\text{ cm} \times 70\text{ cm}$ styrofoam panels) controlled by motors to move independently between retracted and extended positions (Fig. 1). When extended, each obstacle served to block a specific stepping movement, i.e. a forward step with the right or left foot or a lateral step to the right or left side. For safety, the obstacles were designed to give way if struck and a harness was worn to prevent falling.

To maximize the novelty and unpredictability of the perturbation and environment, subjects performed only one trial (first exposure to the platform motion; no prior knowledge of direction, speed or timing) and were not permitted to view the enclosed platform area prior to the start of the trial (guided onto platform with eyes closed). They were told: (1) the platform would move suddenly sometime within 1 min after opening their eyes; (2) the platform motion could cause them to fall forward, backward, left or right; (3) objects on the platform might change position; (4) they could look about and do whatever came naturally to recover balance but should avoid contacting any objects (and should not move feet prior to platform motion).

All four obstacles were initially retracted and began to move intermittently 2.0 s after the instruction to open the eyes, alternating one or more times between retracted and extended positions over an interval of 23.5 s. Each obstacle movement took 3.0 s; between movements, the obstacle remained stationary for 1.5–5.0 s. The trial included intervals where more than one obstacle was in motion. A forward step reaction was evoked by a large backward platform translation [300 ms square-wave acceleration pulse (3.0 m/s^2) followed by a 300 ms deceleration pulse (-3.0 m/s^2); peak velocity 0.9 m/s] delivered 2.0 s after the final obstacle movement. The final obstacle configuration restricted forward motion of the right foot and lateral motion of the left foot (Fig. 1D). Subjects were thus required to use the left foot to execute the forward step, but could not predict this prior to PO (e.g. a lateral crossover step with the right foot would have been required had the perturbation induced a leftward fall).

Bilateral head-mounted video-based eye trackers recorded gaze location (60 Hz). The left tracker was set up to optimize recording of downward gaze shifts, while the right tracker was used primarily to measure gaze in other directions. Each tracker superimposed gaze location on the video image recorded by a 'scene camera' mounted rigidly on the head [31]. These video images were used to determine when visual fixation ($>50\text{ ms}$) of the obstacles, walls or floor occurred. For floor fixations, gaze location was determined relative to a grid marked on the floor (1 cm resolution). An overhead video camera was

used to resolve the step-landing site (marker on great toe) relative to this same grid (to allow direct comparison with the gaze-location data), and to determine whether obstacle contact occurred. Foot-off and foot-contact times were determined from vertical ground-reaction forces ($<$ or $>5\%$ body weight, respectively) measured by two force plates built into the platform surface; an accelerometer mounted on the platform was used to determine PO (0.1 m/s^2) (all signals sampled at 200 Hz). Although subjects often took multiple steps to recover equilibrium (6/12 YA, 10/10 OA), our focus was on the initial step.

The Fisher Exact Test (FET) was used to examine whether one age group was more likely than the other to: (1) initiate a downward saccade after PO, (2) be looking downward at time of foot-contact, or (3) avoid contact with the obstacle by stepping with the correct (left) leg. In addition, one-way analysis of variance was performed to analyze age-related differences in: (1) number of pre-perturbation saccades, (2) percentage of pre-perturbation time in which gaze was fixated on specific areas (i.e. floor, forward walls, obstacles), (3) timing of post-perturbation saccades, and (4) timing of foot-off and foot-contact. Within each age group, a one-tailed, one-sample binomial test was applied to determine whether the percentage of subjects who avoided obstacle contact by stepping with the correct (left) leg was significantly greater than the 50% success rate that would have occurred by chance alone.

As hypothesized, young adults never redirected gaze to the obstacles, step foot or step-landing site between the time of PO and the completion of the initial stepping reaction, yet were typically able to select the correct (left) leg for the step to avoid obstacle contact (10 of 12 cases). The frequency of correct responses (83%) was significantly greater than the 50% success rate that would occur by chance ($Z=2.53$; $p=0.02$). Nine of the 10 subjects who stepped with the correct (left) leg actually did initiate a saccade after PO, but the new gaze location was consistently anterior to the eventual step-landing site. The one subject who did not make a saccade was already looking at a similar location at time of PO. For the 10 subjects who stepped with the leg left, the antero-posterior distance between point of gaze at time of foot-contact and landing site (great toe) ranged from 5 to 80 cm (mean \pm S.D.: $38 \pm 25\text{ cm}$; Fig. 1D). The two young adults who stepped with the right leg (and consequently hit the obstacle) were both looking at the floor at time of PO, and did not initiate a saccade in response to the perturbation. Similar to the others, their gaze was fixated anterior (36–64 cm) to the eventual step-landing site.

Contrary to our hypothesis, the older adults were also typically able to select the correct stepping leg (9 of 10 cases). Their success rate (90%) was significantly greater than the 50% rate that would occur by chance ($Z=2.31$; $p=0.01$), and did not differ significantly from the 83% success rate of the young adults (FET $p>0.999$). Like the young adults, the older subjects accomplished this without looking at the swing foot, obstacles or eventual step-landing site during the step. However, in contrast to the tendency of the young adults to look at a location on the floor anterior to the step-landing site, the older adults were more likely to be looking forward at the platform walls at

time of foot-contact (9/10 OA looked forward at the walls, versus 0/12 YA; FET $p < 0.00002$). Only two of the older subjects made a saccade to the floor in response to the perturbation, and one of these subjects quickly redirected gaze to the front wall. Two other subjects made a saccade directly to the front wall, as did the one subject who stepped with the incorrect leg. The remaining five older adults were looking forward at the walls at time of PO, and continued to do so during the step reaction. Overall, there appeared to be a trend for the older adults to be less likely than the young to initiate a saccade after PO (5/10 OA, 9/12 YA; FET $p = 0.08$).

There was no evidence to suggest that older adults might have delayed initiation of their stepping reactions to allow more time for visuospatial processing. Both age groups showed similar and rapid timing of foot-off [OA 402 ± 48 ms, YA 415 ± 92 ms; $F(1, 20) = 0.19$, $p = 0.67$] and foot-contact [OA 549 ± 61 ms, YA 574 ± 92 ms; $F(1, 20) = 0.53$, $p = 0.47$]. There was also no evidence that the ability of the older adults to acquire ‘online’ visuospatial information was compromised due to an age-related slowing in the oculomotor system. For the five older subjects who executed post-perturbation saccades, the saccade was completed 178 ± 97 ms after PO, compared to 232 ± 148 ms in the nine young adults who made post-perturbation saccades [$F(1, 12) = 0.17$, $p = 0.69$]. Saccades were completed prior to foot-off (8/9 YA, 4/5 OA) or very shortly (< 27 ms) thereafter. There was no age-related difference in the time between saccade-completion and foot-off [YA 230 ± 168 ms, OA 161 ± 165 ms; $F(1, 12) = 0.53$, $p = 0.48$] or foot-contact [YA 385 ± 169 ms, OA 311 ± 169 ms; $F(1, 12) = 0.34$, $p = 0.57$].

During the 23.5 s interval prior to PO, all subjects engaged in visual scanning of their surroundings and made numerous saccades between the walls, floor and obstacles. Although the number of gaze shifts between surfaces (walls, floor or obstacles) was no different in the two age groups [OA 19.1 ± 10.0 , YA 23.5 ± 5.9 ; $F(1, 20) = 0.57$, $p = 0.46$], the older adults tended to direct gaze forward prior to the perturbation. On average, they spent nearly half the time ($47 \pm 32\%$) looking forward at the walls, whereas young adults looked in this direction only $7 \pm 7\%$ of the time [$F(1, 20) = 17.4$, $p = 0.0005$] and spent a much greater proportion of time looking at the front obstacles [YA $47 \pm 9\%$, OA $27 \pm 21\%$; $F(1, 20) = 5.82$, $p = 0.03$] and side obstacles [YA $18 \pm 12\%$, OA $5 \pm 6\%$; $F(1, 20) = 10.1$, $p = 0.004$].

The hypothesized use of previously acquired spatial information to select the correct (left) leg to step implies that the final position of the left-front obstacle was updated prior to PO. This information could be acquired directly by viewing the obstacle in its final position, or inferred by viewing movement of the obstacle toward this position. In support of the hypothesis, all 19 subjects who stepped correctly did fixate the left-front obstacle during or after its final retraction, and hence had access to foreknowledge that the left foot could be moved forward without obstruction. However, the three subjects who stepped with the incorrect (right) leg did so despite access to such foreknowledge (having fixated the final retraction of the left-front obstacle), and two of the three did so despite access to foreknowledge that forward movement of the right foot was blocked (having fixated the final extension of the right-front obstacle).

The ability of the subjects to avoid obstacle contact without directing gaze at the foot, step-landing site or obstacles at any time after PO argues against ‘online’ visual control of the step initiation. Instead, it appears that an appropriate step reaction was initiated after PO by combining ‘stored’ visuospatial information about the surroundings (acquired prior to PO) with post-PO feedback about the perturbation-induced body motion. The findings cannot be attributed to a predictive control strategy, as the obstacle configuration and uncertainty regarding perturbation direction precluded ability to predict the required (left) step-leg prior to PO. Although it is possible that subjects “guessed” which leg to use, the high success rate is not consistent with random selection, and the use of the left leg actually conflicts with the natural tendency to step with the dominant (right) leg (95% of trials in one study [21]). Furthermore, post hoc analysis of preparatory limb unloading gave no indication that subjects preplanned to step with the left leg (percent of body weight supported by left leg immediately prior to PO: $49.7 \pm 7.1\%$; range 29–69%).

These findings are consistent with the aforementioned theory that a pre-formed spatial map is used to guide the balance-recovery reaction. Previous studies supporting this theory involved repeated trials in a static environment and hence did not require continual updating of a spatial map [7,31]. The present findings demonstrate that the CNS does indeed monitor ongoing changes in environmental features via overt visual scanning of the surroundings. Furthermore, the results indicate that the acquired visuospatial information was used to help guide the stepping reaction evoked by a subsequent perturbation in the majority of subjects. The fact that three subjects failed to avoid obstacle contact, despite looking at the final obstacle configuration, suggests that factors other than gaze behavior (e.g. attention, spatial memory) may affect whether sampled visuospatial information is incorporated into subsequent balance-recovery reactions.

This apparent use of ‘stored’ visuospatial information to control the stepping reaction may appear similar to the control strategy used in accommodating static obstacles during gait, i.e. the use of visual constraint information that is acquired in advance of the obstacle-clearance (or avoidance) step [6,10,25]. There are, however, some important distinctions. For perturbation responses, the visuospatial information about the surroundings is presumably sampled and stored as a contingency, for use in the event that a sudden loss of balance occurs. In contrast, for volitional stepping, the sampled visuospatial information can be immediately incorporated into the preplanning of the obstacle-avoidance response. Such preplanning is not possible in responding to an unpredictable perturbation, because the visuospatial constraint information must be stored until it can be integrated (after PO) with ‘online’ multisensory feedback about the direction, amplitude and speed of the perturbation-induced body motion (which dictates the required direction, amplitude and speed of the step). In terms of the need to react rapidly, perturbation-evoked stepping reactions may actually have more in common with the very rapid step adjustments that can accommodate the sudden appearance of an obstacle immediately in front of the foot during gait [30]; however, such responses pre-

clude the possibility of using ‘stored’ visuospatial information, forcing instead a reliance on ‘online’ feedback from the central and/or peripheral fields [20].

A surprising finding was that the gaze of young adults was consistently directed (after PO) at a location on the floor that was substantially anterior to the eventual step-landing site. It may be that the anterior location of the fixation site served to provide visuospatial information about the floor surface beyond the initial step location, in anticipation that additional steps might be required to recover equilibrium. This would be similar to the forward-directed gaze behavior that occurs when walking in a cluttered environment [12,26]. If gaze is not directed too far ahead of the stepping leg, there is also the potential to use peripheral vision to aid in making final adjustments to the foot landing [20]. In addition, a more anterior fixation point may enhance ability to acquire self-motion information via lamellar or shear optic flow [3]. Optic flow has, in fact, been shown to affect perturbation-evoked stepping [14].

Interestingly, the older adults tended to direct gaze at the front wall, rather than the floor, after PO, and also spent less time than the younger subjects looking down or to the side to examine the environment prior to the perturbation. This gaze behavior may reflect a strategy to enhance stability by minimizing eye and head motion. Although we did not measure head motion, it is known that head movements often accompany even small gaze shifts [2,17], and substantial head rotation was clearly required to fixate the side obstacles. Reduction in head motion could enhance balance control by increasing the accuracy of vestibular cues [13,23] and by facilitating ‘top-down’ control strategies that require the head to serve as a stable ‘sensory platform’ [5,24]. Restriction of eye and/or head movements would also reduce the destabilization that can be induced by such movements [15,16], and would minimize changes in gaze- or head-centered reference frames that could impede egocentric ‘mapping’ of the surroundings [1,9]. The more restricted gaze behavior of the older adults did not compromise ability to select an appropriate leg for the initial step in the present study, but could conceivably lead to problems in monitoring more complex environments.

In conclusion, the results provide evidence that the initial stages of balance-recovery reactions were modulated on the basis of visuospatial information about environmental constraints that was acquired and updated on an ongoing basis prior to PO, as opposed to relying on ‘online’ visual feedback. The capacity to do this was not adversely affected by aging, but could conceivably be compromised when the environment is more complex or there are competing attentional demands that interfere with monitoring of the environment. Further research is needed to examine these possibilities, to understand the determinants of the gaze behavior that occurred subsequent to PO, and to explore possible relationships between the gaze behavior and other aspects of the postural response (e.g. the need to take multiple steps to recover equilibrium).

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