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RESEARCH ARTICLE

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Redirection of gaze and switching of attention during rapid stepping reactions evoked by unpredictable postural perturbation

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Abstract In many situations successful execution of a balance-recovery reaction requires visual information about the environment. In particular, reactions that involve rapid limb movements, such as stepping, must be controlled to avoid obstacles and accommodate other constraints on limb trajectory. However, it is unknown whether the central nervous system can acquire the necessary visuospatial information prior to perturbation onset or must, instead, redirect gaze at the floor during the execution of the stepping reaction. To study this we examined gaze behaviour, during rapid forward-directed stepping reactions triggered by unpredictable platform perturbation, in 12 healthy young adults. We also monitored switching of attention, as inferred from onset of significant error in performing a concurrent visuomotor tracking task. Obstacles and/or step targets were used as constraints, to increase demands for accurate foot movement. Downward gaze shifts towards the floor almost never occurred during stepping reactions when foot motion was unconstrained but did occur more frequently as the demands for accurate foot movement increased. Nonetheless, even in the most challenging condition (target plus obstacle), downward redirection of gaze occurred in less than 40% of the trials, and subjects were commonly well able to clear the obstacle and land the foot on the target without redirecting their gaze towards the floor. An apparent switching of attention, subsequent to perturbation onset, occurred frequently ($>80\%$ of trials) in all task conditions, independent of the gaze shifts. The findings indicate that visual fixation of the foot or floor was not essential for accurate control of the foot movement, nor was the apparent switching of attention that followed perturbation onset linked, in any consistent way, to overt changes in visual fixation. Spatial features of the support surface were apparently "remembered" prior to perturbation onset, thereby allowing both vision and attention to be directed to other demands during the execution of the balance reaction.

Keywords Attention · Balance · Environmental constraints · Eye movements · Postural control · Stepping · Triggered reactions · Vision

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Introduction

Numerous studies have demonstrated that vision contributes to the control of postural stability, predominantly affecting slow or low-frequency balance corrections (Diener et al. 1986). However, it would appear that no studies have addressed the potential role of eye movements in acquiring visual information that may be needed to respond effectively to a sudden, unexpected, loss of balance. Visual information about the spatial features of the nearby environment is likely to be of critical importance when the balancing reaction involves limb movements, such as stepping. Rapid, triggered, compensatory, stepping reactions must be directed and scaled appropriately in order to arrest the centre-of-mass motion suddenly evoked by an unexpected perturbation (Maki and McIlroy 1997, 1999; Hsiao and Robinovitch 1999; Pai 2003), but the control of these reactions must also take into account the location of obstacles and other environmental constraints on foot trajectory and step placement (Zettel et al. 2002a, 2002b; Maki et al. 2003).

These demands suggest a critical role for visual attention, which involves the allocation of cognitive and/or perceptual resources to objects or events in the visual field (Harris and Jenkin 2001) Clearly, it is important for the central nervous system (CNS) to direct visual attention to the immediate environment in order to acquire the spatial information needed to execute compensatory stepping reactions successfully. It is not known, however, whether the CNS is able to acquire the requisite visual information in "real time", after onset of postural perturbation. An alternative possibility is that this information is acquired prior to perturbation onset and subsequently integrated with on-line sensory feedback about the body motion induced by the perturbation. This control strategy would have the advantage of avoiding potential delays in initiating the response (associated with time required to plan and execute eye and/or head movements to acquire the visual information and then process this information) but would, instead, necessitate reliance on a pre-formed egocentric spatial map of the immediate environment, which would have to be updated automatically as we move about in our daily lives (Colby 1998; Ghafouri et al. 2004).

It is also possible that the CNS uses eye movements towards the anticipated landing site to help guide the foot trajectory and step placement during the execution of the stepping reaction. This would be consistent with findings from studies of targeted volitional stepping movements, which suggest that a saccade towards the step target is used to guide feedforward control of the foot movement (Hollands and Marple-Horvat 2001; Di Fabio et al. 2003). Interestingly, the timing of this saccade, which typically occurred prior to foot off during these self-initiated volitional movements (Hollands et al. 1995; Hollands and Marple-Horvat. 1996), appears to be similar to the timing at which we have observed an apparent switching of attention during rapid stepping reactions that are triggered by postural perturbation (Maki et al. 2001a). However, we did not record eye movements in that study. As a result, it is not clear whether the switching of attention was associated with redirection of gaze and acquisition of new visual information or whether, instead, this reflected re-allocation of cognitive resources for other purposes (e.g. to process sensory information related to the perturbation-induced body motion and to plan the stabilizing motor response).

In the present study we examined whether gaze is redirected downwards, towards the feet or floor, during the execution of forward-directed compensatory stepping reactions evoked by unpredictable postural perturbation. We also examined the timing of any such gaze shifts in relation to the apparent switching of attention that typically occurs prior to foot off during such reactions (Maki et al. 2001a). We sought to determine whether: (1) the CNS can acquire the necessary visual information about environmental constraints prior to perturbation onset or must, instead, redirect gaze at the floor surface during the execution of the reaction; (2) any such need to redirect gaze during the reaction is influenced by increasing demands for accurate control of the foot trajectory; (3) the switching of attention that typically precedes foot lift is associated with changes in gaze direction. The findings will be shown to support the view that on-line visual control is not required to meet demands imposed by nearby constraints, and that the switching of attention that follows onset of postural perturbation is not related to on-line acquisition of visuospatial constraint information. Rather, it appears that spatial information about environmental constraints can be acquired beforehand, stored in memory, and then used after perturbation onset to aid in guiding the foot trajectory.

Methods

Subjects

Twelve healthy, naive, young adults were tested (five male, seven female; ages 22–29 years, height 160 cm–

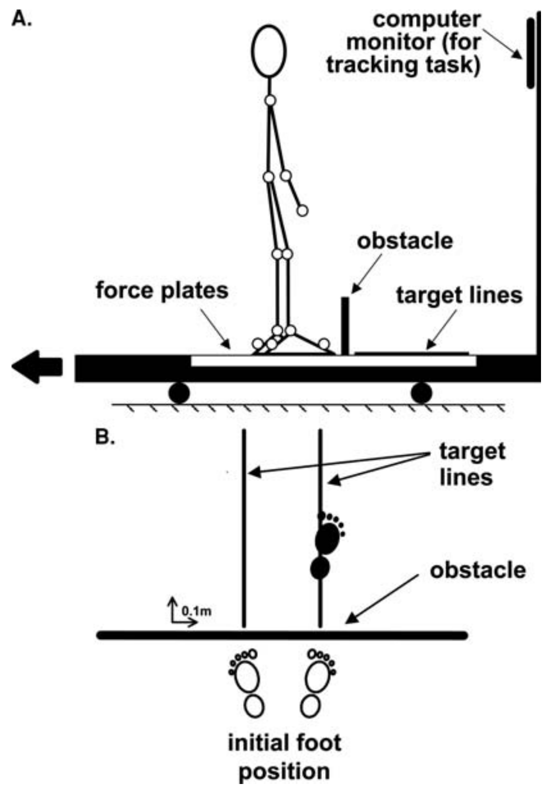


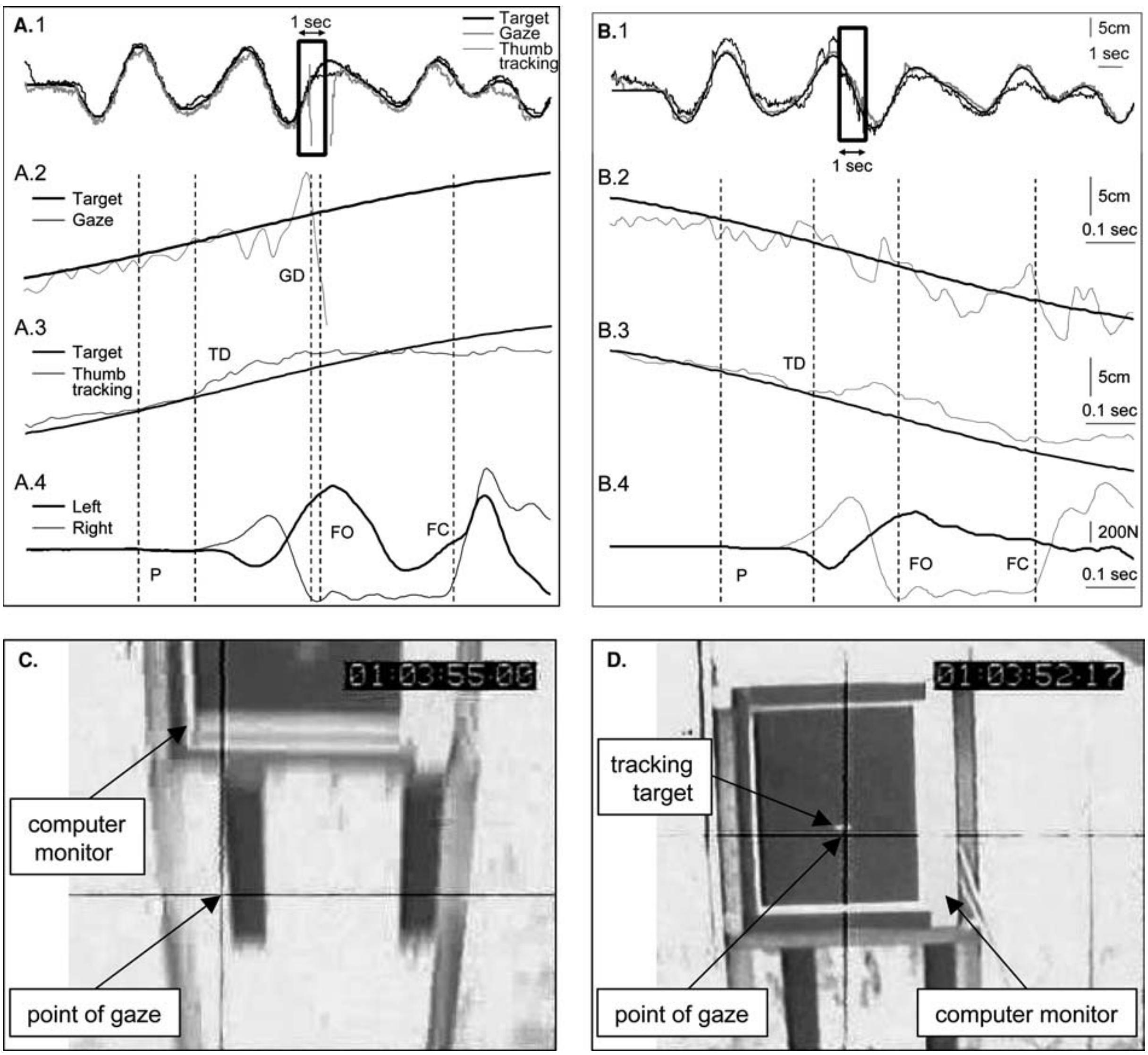
Fig. 1 Schematic drawings of the obstacle and step targets, as seen from a side view (**a**) and overhead view (**b**) of the moving platform. The obstacle height and the location of the obstacle and target lines, in relation to the subject, are drawn approximately to scale. The *large arrow* denotes the backward direction of platform motion used to evoke the forward-step reactions

181 cm, mass 54 kg–93 kg). All were right-hand and right-leg dominant (as determined by preferred limb for writing and kicking, respectively) and reported no medical conditions affecting balance. The subjects were required to have a minimum uncorrected visual acuity of 20/40 (Snellen chart); we excluded those who required corrective lenses, to avoid potential problems in using the eye tracking apparatus. Each subject provided written informed consent to comply with ethics approval granted by the institutional review board.

Protocol

Compensatory stepping reactions were evoked by sudden, unpredictable horizontal movement of a large (2 m × 2 m), computer-controlled, moveable platform (Maki et al. 2003; Fig. 1a). Subjects began all trials in a standardized comfortable foot position (McIlroy and Maki 1997) at the centre of the platform. For safety, they wore a harness designed to prevent falls without providing somatosensory feedback that might influence balance control, and safety guardrails and walls were mounted around the platform perimeter. The focus of the study was on forward stepping reactions evoked by large backward platform translations (average acceleration 3.0 m/s^2, peak velocity 0.9 m/s, duration 0.6 s); however, other perturbation directions and magnitudes were included for unpredictability. Each block of trials comprised, in random order, six large backward platform translations, two "catch" trials (no platform motion) and eight additional platform translations of various directions (forwards, backwards, left or right) and magnitudes (0.13 m/s^2–3.0 m/s^2 ; 0.2 m/s–0.9 m/s).

A visuomotor tracking task was performed concurrently so that we could monitor switching of attention during the perturbation reactions (McIlroy et al. 1999; Maki et al. 2001b; Norrie et al. 2002). This task involved pursuit tracking of a continuously moving, pseudo-random target (sum of sines 0.24, 0.28, and 0.42 Hz; see Fig. 2a.1, b.1) displayed for 20 s on a computer screen (1.2 m in front of the subject). The subject controlled the



pursuit cursor by using the right thumb to rotate a potentiometer (splinted to the wrist and supported by a sling and restraining strap that held the hand comfortably in front of the abdomen). Onset of significant error in tracking performance, subsequent to perturbation onset, was inferred to reflect switching of attention from the tracking task to the balance-recovery task. The timing of perturbation onset was varied unpredictably; however, to facilitate accurate detection of perturbation-related tracking deviation, the perturbations were always delivered during relatively straight sections of the target waveform, where unperturbed tracking accuracy is highest. Practice "tracking-only" trials ($n = 6$) preceded the perturbation trials. An additional 16 tracking-only trials (performed at start, midpoint and end of session) were used to determine the thresholds for onset of significant tracking deviation (see Maki et al. 2001b for details).

Blocks of trials were performed for each of four environmental-constraint conditions (Fig. 1): (1) *no constraint*, (2) *obstacle only*, (3) *target only*, and (4) *obstacle plus target*. The obstacle was a styrofoam-covered metal bar (3.5 cm diameter, 150 cm length) that was mounted transversely on the moving platform, in front of the subject (2.5% of body height from the toes) at a height equal to 12.5% of body height; a block of foam rubber (2.4 cm thick) filled the gap between the bar and the platform surface. In the target tasks a line of red tape (2 cm × 75 cm), extending forwards in front of each foot, was used to indicate the required medio-lateral (m-l) step placement (forward step length was left unrestricted so as not to compromise the subject's ability to arrest the forward perturbation-induced body motion). At the start of each trial block, the subject's attention was directed to the constraint conditions when the task instructions were given. The subject was also free to look at the floor during the interval between trials (approximately 30 s). However, once a trial had started and the subject was performing the tracking task, it was not possible to see the obstacle or step targets (in the central or peripheral fields) without redirecting gaze downwards, away from the tracking-task display.

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Fig. 2 Example data from one subject. Data are shown for an obstacle-plus-target trial (**a**) and an obstacle-only trial (**b**), where significant tracking deviation was (**a**) or was not (**b**) accompanied by downward gaze shift towards the floor. Plots a.1 and b.1 each display the recorded point-of-gaze and thumb-tracking signals, superimposed on the tracking target waveform, for the full 20-s duration of the trial. The target moved vertically up and down on the computer screen located in front of the subject; the plots display the vertical position of the point-of-gaze and thumb-tracking cursor in relation to the screen. The *rectangular box* in plots a.1 and b.1 indicates a 1-s time window during which the platform perturbation was delivered. Plots a.2–a.4 and b.2–b.4 are enlargements of this 1-s time window. Plots a.2/b.2, a.3/b.3, and a.4/b.4 display the vertical point-of-gaze signal, vertical tracking (*cursor position*) signal, and vertical ground-reaction forces, respectively. The calibration (*scaling*) markings displayed along the right edge of **b** also apply to **a**. *Vertical broken lines* marked *P*, *TD*, *GD*, *FO*, and *FC* indicate time of perturbation onset, onset of significant tracking deviation, onset of downward gaze deviation, foot off, and foot contact, respectively. Note that the onset of tracking deviation, prior to foot off, occurred in the complete absence of any downward gaze shift throughout the duration of the stepping reaction (trial depicted in **b**), or preceded the gaze shift by a substantive (~300 ms) time interval (trial depicted in **a**). For the display of the point-of-gaze data in **a** and **b**, kinematic measurements of head position and orientation (Flock of Birds; Ascension Technology, Burlington, Vt., USA) were integrated with the corneal reflection signals indicating gaze direction relative to the head. However, as detailed in the Methods, a simpler video-based method was used in the actual analysis of the gaze-shift data. **c** and **d** illustrate the video-based approach: cross-hairs indicating the point of gaze are superimposed on the video-image recorded by a head-mounted "scene" camera. The example video-frames shown in **c** and **d** illustrate the gaze behaviour occurring shortly after foot off for the trials depicted in **a** and **b**, respectively. Note that gaze remains directed at the tracking display in **d**, whereas in **c**, gaze has begun to move downwards due to a combination of head movement (indicated by the change in scene) and eye movement (indicated by the change in crosshair position relative to the scene-camera field of view)

Each subject performed two blocks of randomized trials (16 per block) for each of the four constraint conditions, the order counterbalanced both within and across subjects. Two large backward-translation trials preceded the first block of randomized trials. Trials alternated between tracking and no tracking (subjects looked straight ahead at a static visual target on the computer screen). The no-tracking trials were included to allow comparison with previous studies and will not be discussed further here. The protocol yielded 25 large-backward-translation tracking trials per subject, all of which involved forward-stepping reactions. These trials were the focus of the analysis.

Vigilance to the tracking task was encouraged by a monetary reward. Subjects were told to do whatever came naturally to prevent falling, but they invariably stepped in the large-perturbation trials. For constrained trials, they were told to avoid contacting the obstacle and/or to direct the step (if they needed to step) so as to land the great toe on the target tape, and that failure to do so would be penalized (reducing their chances of winning the monetary reward for best tracking performance).

Measurements and analysis

A lightweight, video-based eye tracker (model 501, Applied Science Laboratories, Bedford, Mass., USA) was worn on the head and used to record movements of the left eye at a sampling rate of 60 Hz. This system uses infra-red corneal reflections to determine the gaze direction, relative to the head. It displays this information as cross-hairs (indicating the horizontal and vertical position of the point of gaze) that are superimposed on the video-images recorded by a "scene camera" mounted rigidly on the head (see Figs. 2c, d). The scene camera records changes in the field of view resulting from changes in head position and orientation, and the cross-hairs displayed on the video-image indicate the object in the environment at which gaze is directed. By playing back these video-images frame by frame, we were able to determine whether the subject looked downwards towards the floor following perturbation onset (using head and/or eye movements), as well as the onset time of each such downward gaze shift (to within 16 ms). The same method was used by Patla and Vickers (1997) in a study of obstacle avoidance during gait.

We determined the onset of significant error in the tracking task by comparing the tracking performance with the thresholds determined from the tracking-only trials (see Maki et al. 2001b for details). Two force plates, embedded flush with the surface of the moving platform, were sampled at 200 Hz to determine time of foot off and foot contact (swing foot unloading or reloading $<5\%$ or $>5\%$ of body weight). Video-recordings from four overhead cameras were used to identify obstacle contact, 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), and to verify foot off and foot contact times determined from the force plates. All timing values were defined relative to onset of platform acceleration (0.1 m/s^2), as recorded by an accelerometer. Only gaze and tracking deviations that occurred prior to foot contact were considered. Example tracking, gaze and force-plate data are shown in Fig. 2.

For five subjects, electromyographic (EMG) activity was recorded by surface electrodes placed over the right extensor digitorum muscle so that we could check for the presence of perturbation-evoked activation that could potentially interfere with the performance of the visuomotor tracking task (McIlroy and Maki 1995). The EMG signal was bandpass filtered (10 Hz–500 Hz) and sampled at a rate of 1,000 Hz. Onset of significant activation was detected by a computerized algorithm (rectified magnitude >3 standard deviations above pre-perturbation level for >25 ms) and confirmed by visual inspection.

Repeated-measures analysis of variance was performed to assess the effect of constraint condition on frequency and onset timing of downward gaze shift and tracking deviation during stepping. For the frequency analyses, the dependent variable was the percentage of trials (as determined within each subject, for each of the four task conditions) in which gaze shift or tracking deviation occurred. Of the 300 trials potentially available for analysis, two were excluded because a subject misunderstood instructions, and another trial was dismissed because a subject stepped high as if to clear an obstacle even though no obstacle was present. In addition, due to technical problems, gaze data were not available for five trials and tracking data were not available for 12 trials.

Results

Gaze redirection

The redirection of gaze towards the floor, during the stepping reactions, was highly dependent on the constraint condition, and occurred more frequently as the demands for accurate control of the foot movement increased ($F(3,33) = 8.04$, $P = 0.0004$; Fig. 3). In the most demanding task, involving the obstacle and step target, there was a gaze shift towards the floor, prior to foot contact, in 37% (27/73) of trials. This rate dropped to 24% (16/68) when only the step target was present. Downward gaze shift almost never occurred in the absence of the step target (3 of 70 *obstacle-only* trials; 1 of 69 *no-constraint* trials). The tendency to look down was primarily limited to six subjects, who each looked down in four or more of the 12 step-target trials. Of the remaining subjects, four looked down in only one of these trials and two did not look down at all. There was no evidence of substantive changes in gaze behaviour due to increasing familiarity or "practice" effects: subjects were equally likely to look downwards in their first

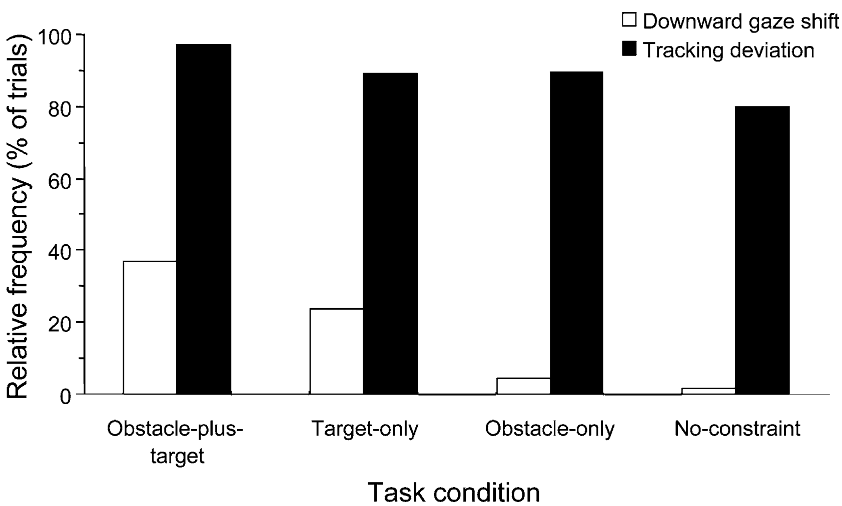

Fig. 3 Relative frequency of downward gaze shift and tracking deviation, according to constraint condition. Each *bar* represents the percentage of trials in which a downward gaze shift or tracking deviation occurred. Note the high frequency of tracking deviation, across all conditions, and the much lower frequency of gaze shifts. Note also that the gaze shifts were almost entirely limited to the conditions that involved the step target

three trials involving the step target as in their last three step-target trials (in each case 12 of 36 trials).

The timing of the downward gaze shift varied widely, with onset times ranging from 140 ms to 710 ms after perturbation onset. On average, however, the change in gaze direction occurred around the time of foot off, nearly 300 ms prior to foot contact (Fig. 4a, b; see also Fig. 2a.2). In relation to perturbation onset, the gaze shift actually began more than 100 ms earlier, on average, in the *target-only* trials, than in the *obstacle-plus-target* trials: 337 ± 119 ms (mean ± SD) vs 449 ± 159 ms ($F(1,5) = 5.96$, $P = 0.05$). In relation to foot contact, the difference in gaze-shift timing was somewhat less pronounced: onset of gaze shift preceded foot contact by 224 ± 131 ms in *target-only* trials, vs 287 ± 157 ms in *obstacle-plus-target* trials ($F(1,5) = 1.67$, $P = 0.23$). This latter finding reflects the fact that foot contact occurred much later in the *obstacle-plus-target* trials (560 ± 76 ms vs 737 ± 130 ms; $F(1,5) = 17.9$, $P < 0.008$), due to the large increase in swing duration required to step over the obstacle (Fig. 4b).

Gaze redirection had no effect on the ability to avoid the obstacle. The obstacle was cleared successfully (without contact) in 97% of trials regardless of whether subjects did or did not look downwards (successful clearance in 29 of 30 gaze-shift trials and 110 of 113 no-shift trials). On the other hand, downward gaze deviation did appear to improve ability to land the foot on the step target. For *target-only* trials the success rate was 81% (13/16) when subjects looked down prior to foot contact vs 52% (27/52) when they did not look down. There was a similar improvement in success rate during *obstacle-plus-target* trials: 74% (20/27) when looking down vs 48% (22/46) when no downward gaze shift occurred. Mean absolute step-to-target error (|m-l distance| from great toe to target tape) improved by 2 cm when downward gaze shift did occur (21 ± 20 mm vs 41 ± 39 mm). "Practice" appeared to lead to some small improvements in ability to land on the target. When the first three step-target trials were compared with the last three, success rates were 75% (9/12) vs 83% (10/12) in trials where gaze shift occurred and 29% (7/24) vs 46% (11/24) in trials where subjects did not look downwards.

Attention switching

An apparent switching of attention from tracking task to balance-recovery task (as reflected by sudden significant deviation in tracking performance, e.g. Fig. 2a.3, b.3) followed perturbation onset in 84% (235/280) of trials, while 9% (26/280) of trials had no tracking deviation (in 19 trials, tracking performance was too inconsistent to allow onset of perturbation-related

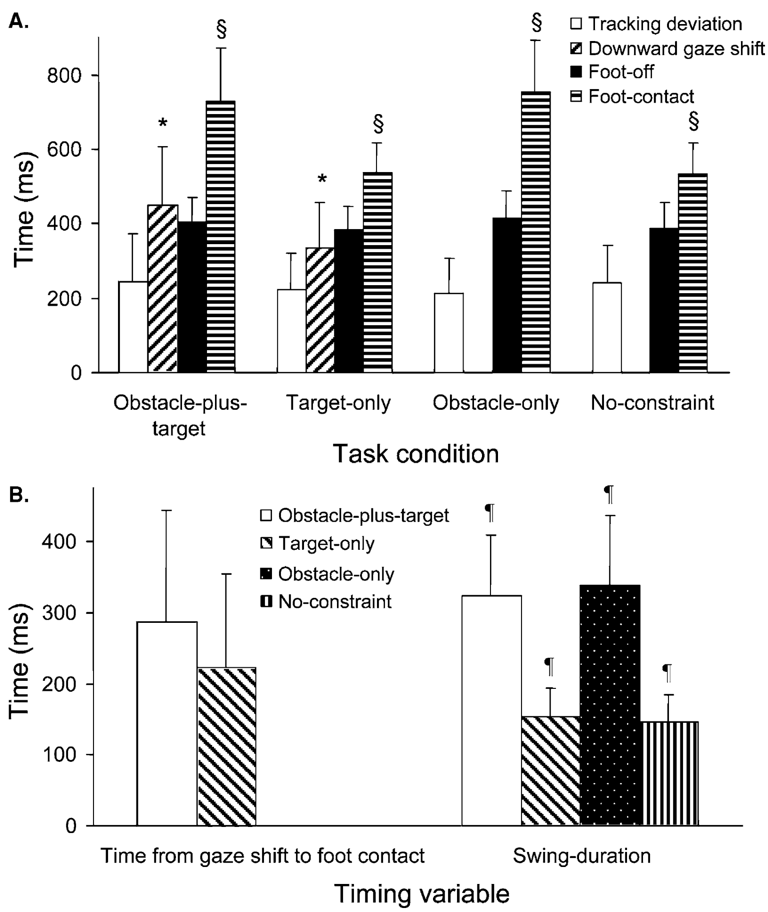

Fig. 4 Timing of key events. **a** Mean time of foot off, foot contact, onset of downward gaze shift, and onset of tracking deviation is shown for each of the four constraint conditions, with *error bars* indicating the standard deviation. Note that tracking deviation consistently began prior to foot off, in all constraint conditions. No gaze-timing data are shown for the no-target tasks because gaze shift was almost exclusively limited to the two tasks involving the step target (even in these tasks, gaze shift occurred in a minority of trials, as indicated in Fig. 3). In the few trials where downward gaze shift did occur it began 112 ms earlier, on average, in the *target-only* task than in the *obstacle-plus-target* task (*$P < 0.05$). **b** Time interval by which the onset of gaze shift preceded foot contact, as well as the swing duration (time interval between foot off and foot contact). Note that foot contact was delayed in the obstacle trials (see **a**; § $P < 0.05$) because a much prolonged swing duration was needed to clear the obstacle (**b**; ¶ $P < 0.05$)

tracking deviation to be determined reliably; these trials were omitted from the tracking-related analyses). Although tracking deviation occurred with high frequency in all constraint conditions (Fig. 3), there was a small but significant constraint-related effect ($F(3,33) = 3.05$, $P = 0.04$), with tracking deviation occurring most consistently in the most demanding task (69 of 70 *obstacle-plus-target* trials; 99%) and least consistently in the least demanding task (51 of 63 *no-constraint* trials; 81%). The frequency of tracking deviation in the other two conditions was at an intermediate level (91%, 59/65, for *obstacle-only* trials; 89%, 56/63, for *target-only* trials).

The average onset time of tracking deviation was 231 ± 107 ms and did not differ significantly between constraint conditions ($F(3,32) = 0.94$, $P = 0.43$; Fig. 4). As in our previous study of attention switching during compensatory stepping (Maki et al. 2001a), the tracking deviation almost always began prior to foot off (217 of 235 cases; 92%). The average interval between onset of tracking deviation and foot off was 165 ± 110 ms.

An absence of attention switching, as inferred from an absence of tracking deviation, did not appear to compromise ability to contact the step target or avoid the obstacle. Average absolute step-to-target error was 34 ± 34 mm in trials with tracking deviation ($n = 125$) vs 35 ± 29 mm in the eight step-target trials where tracking deviation did not occur. For obstacle trials, successful obstacle clearance occurred in 98% (125/128) of trials with tracking deviation vs 100% (7/7) of trials where tracking deviation did not occur.

The immobilization of the tracking arm appeared to be effective in inhibiting perturbation-evoked reactions in the distal arm muscles; hence, it is unlikely that the attention-switching results were confounded by "motor interference". Performance of the tracking task required continuous activation of the extensor digitorum muscle, which we monitored in five of the subjects. Previous studies have shown that postural perturbation can evoke a burst of activity in this muscle (Maki and McIlroy 1997); however, this was typically absent in the present trials. Within the 111 trials where extensor digitorum EMG was monitored and tracking deviation occurred, there was no perturbation-related activation in 86 cases (76%). For the 25 trials where the perturbation did evoke a burst of extensor digitorum activity, the onset of the burst occurred after the onset of tracking deviation in five cases. This left only 20 of 111 trials (18%) where the perturbation-evoked reaction could have potentially caused the tracking deviation.

Relation between gaze redirection and attention switching

There was a total of 261 trials where the presence or absence of tracking deviation and gaze shift could both be determined reliably. Evidence of attention switching (i.e. significant tracking deviation) occurred in 90% (235/261) of these trials, but gaze shift was detected in only 19% (45/235) of the tracking-deviation trials. While aversion of gaze from the computer screen would obviously be a cause of subsequent tracking error, the start of the gaze shift preceded (or coincided with) the onset of tracking deviation in only ten trials. In the remaining 35 trials the tracking deviation preceded gaze deviation (mean latency 220 ± 116 ms vs 420 ± 150 ms); however, there was little evidence of the consistent temporal coupling that would be expected if the attention switching were related to the motor control of the gaze shift or the subsequent acquisition of new visual information. The time interval between the onset of tracking deviation and subsequent gaze shift was not at all consistent and varied widely among trials (SD 127 ms, range 6 ms–503 ms) (see Fig. 5).

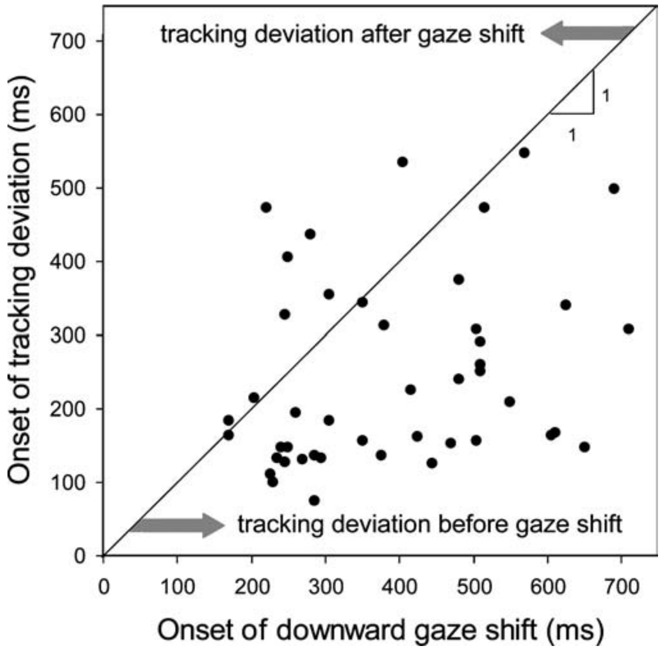

Fig. 5 Scatter plot showing the absence of a consistent temporal relationship between gaze shift and switching of attention (as inferred from onset of significant tracking deviation). Onset of tracking deviation is plotted against onset of downward gaze shift for the 45 trials where both gaze shift and tracking deviation were observed. For values that fall below the superimposed line (79% of trials), the tracking deviation began before the start of the downward gaze shift; hence, the tracking error cannot be explained by the aversion of gaze away from the tracking display in these trials. More generally, the wide variation in the relative timing of the two events would appear to rule out any consistent causal link

Discussion

The present study is, to our knowledge, the first to examine the potential role of eye movements in guiding the selection and execution of balance-recovery reactions. The findings indicate that visual fixation of the foot or floor is not required for accurate control of the foot movement during the execution of rapid, perturbation-triggered stepping reactions. Even when demands for accurate limb movement were increased by means of an obstacle and/or step target, subjects were commonly able to avoid the obstacle and/or land on the target without looking downwards. Although the CNS is able to acquire substantial information about objects that are located in the peripheral visual field (Lyon 1990), it was not possible for subjects in the present study to see the obstacle or step targets, in any part of the visual field, without redirecting gaze downwards (away from the eye-level tracking display). The finding that gaze redirection commonly did not occur during the stepping reactions is therefore consistent with the view that the required spatial information about environmental constraints can be acquired beforehand, stored in memory and then used after perturbation onset to aid in guiding the foot trajectory. It should be noted, however, that these conclusions are specific to the current experimental conditions, i.e. relatively simple environmental constraints that remained static over the course of repeated trials. Ongoing work is addressing whether similar gaze behaviour occurs when responding to postural perturbation in more complex, dynamic environments.

The findings also indicate that the apparent switching of attention that follows onset of postural perturbation is not related to redirection of gaze. Evidence of attention switching (i.e. significant tracking deviation) occurred in 85% of trials, but gaze shift was detected in only 17% of these trials. When gaze shift did occur, it usually began after the onset of tracking deviation, which would indicate that eye or head movement per se was not the cause of the tracking error. Furthermore, the absence of any consistent temporal coupling between the tracking and gaze deviations would appear to rule out the possibility that the switching of attentional was associated with the motor control of the gaze shift or the subsequent acquisition of new visual information. Rather, it would seem that the attentional demands were primarily associated with other aspects of balance control, likely to be related to the processing of the perturbation-induced sensory discharge (Shumway-Cook and Woollacott 2000; Redfern et al. 2001; Quant et al. 2004) and/or the planning of the foot trajectory (Maki et al. 2001a) or other aspects of the motor response (Rankin et al. 2000; Brauer et al. 2002). A possible relation to foot-trajectory planning is supported by the present findings that the attention switching almost always preceded foot lift and that attention switching was most likely to occur when the constraint conditions demanded the most accurate trajectory control. In any case, the fact that there was seldom a complete cessation of efforts to track the target and that the eye movements often persisted in following the target, even after the onset of significant error in tracking (e.g. see Fig. 2b.2), would suggest that the attention switching involved a partial, rather than complete, re-allocation of cognitive resources to the balance-recovery task.

It has been suggested that the tracking-task paradigm may yield delayed estimates for the onset of attention switching if the tracking involves any feedforward (predictive) control elements (Redfern et al. 2002). Any such feedforward control could cause the appearance of tracking error to lag behind the true onset of attention switching. The pseudo-random target waveforms that were used did, in fact, have certain predictable features that may have allowed subjects to use predictive control over short intervals (e.g. the fact that the target motion must necessarily reverse direction whenever the target approaches the limits of the display monitor). The fact that some subjects were able, in a small number of trials, to track successfully for 50 ms–250 ms after looking away from the target display (see Fig. 5) may reflect a capacity for short-term predictive control. We are currently performing experiments to document the extent to which different subjects are able to use predictive control in our tracking task and to quantify the degree to which the tracking deviation may lag behind the true onset of attention switching. However, it is important to recognize that these issues are unlikely to invalidate the main conclusions of the present study, i.e. that gaze redirection was not required for accurate stepping movement and that the initial switching of attention that followed perturbation onset was typically not related to redirection of gaze. In fact, if the true onset of attention switching did occur earlier than the estimates derived from the tracking-deviation data, this would serve to further weaken the evidence for any causal association between the gaze shifts and the attention switching, by further reducing the number of trials where the gaze shift preceded attention switching.

It is perhaps surprising that saccades were not consistently used, after perturbation onset, to assist in online control of the foot movement, particularly when required to step to a target. Studies of volitional limb movement would suggest that such eye movements could potentially help to guide the limb toward the target during the perturbation reactions. For example, studies of volitional upper-limb reaching or pointing movements have demonstrated that visual fixation of the target improves movement accuracy (Abrams 1992), and studies of volitional step-to-target movements have suggested that a saccade toward the target, completed prior to foot off or early in the swing phase, is used to control the foot movement (Hollands et al. 1995; Hollands and Marple-Horvat 1996, 2001; Di Fabio et al. 2003). For obstacle clearance, there is apparently less need for precise foot-movement control. Studies of volitional stepping indicate that step height can be exaggerated to guarantee clearance (Chou et al. 1997) and that the required visual information can be acquired prior to initiating the obstacle-clearing step (Patla and Vickers 1997). The present results would suggest that a similar obstacle-avoidance strategy can be used during stepping reactions that are triggered by sudden unpredictable postural perturbation.

There are a number of potential reasons why visual fixation of the target did not occur consistently during the perturbation-triggered stepping reactions. The CNS may actually act to inhibit eye and head movements during stabilizing reactions, since such movements could exacerbate instability (Hunter and Hoffman 2001) or impede ability to acquire spatial orientation or self-motion information from the visual flow (Brandt et al. 1973). It is also possible that difficulty in disengaging attention from the tracking task impeded the redirection of attentional focus to the step target, which some researchers have postulated must precede the saccade to a target (McFadden and Wallman 2001). Although the subjects were told that inaccurate step-to-target performance would be penalized (reducing the chances of winning the monetary reward for most accurate tracking), they may have nonetheless given top priority to the tracking task, and the fact that the tracking target was not extinguished after perturbation onset may have further impeded saccade execution (McFadden and Wallman 2001). As noted earlier, there was, in fact, a tendency for the eye movements often to persist in following the tracking target throughout the trial, even after the onset of significant error in thumb-tracking performance (see Fig. 2b.2).

Because of the rapid speed at which the triggered stepping reactions were completed, one might also anticipate that temporal constraints could impede effective use of visual fixation to guide the foot movement; however, it appears that the CNS is, in fact, capable of initiating the eye movements with sufficient speed. In the *target-plus-obstacle* trials, gaze shifts were initiated nearly 300 ms prior to foot contact, on average. Even in the *target-only* trials, in which foot contact occurred much earlier (560 ms after perturbation onset compared with 740 ms in *target-plus-obstacle* trials), the gaze shifts were still initiated nearly 250 ms prior to foot contact, on average. In individual trials, gaze shifts were initiated as early as 595 ms prior to foot contact. Such ‘‘lead times’’ would appear to be sufficient to enable useful visual information to be acquired. It is well known that the saccadic eye movement itself could be completed in about 50 ms, whereas an interval in the order of 300 ms might be needed for the CNS to extract the required visual information after completion of the saccade (Harris and Jenkin 2001). The functional value of the gaze shifts observed in the present study is supported by the fact that the mean step-to-target accuracy did appear to improve, to some extent, in trials where downward gaze deviation occurred. However, it should be noted that at least some of the gaze shifts that were recorded very likely occurred too late to provide useful information for on-line control of the limb trajectory. In these trials it is possible that the gaze shifts served another purpose, e.g. efforts of subjects to ascertain whether they had been successful in landing on the target.

In spite of the apparent use of gaze shifts to help guide the foot movement in some of the step-target trials, it should be reiterated that subjects were, in the majority of trials, able to avoid the obstacle and/or land on the target in the absence of any downward gaze redirection. This would indicate that ‘‘remembered’’ visuospatial information about the support surface, acquired prior to perturbation onset, was incorporated into the control. The static, unchanging obstacles and targets used in this study may have facilitated the capacity to ‘‘remember’’ this spatial information; however, it is important to recognize that the unpredictable variation in perturbation magnitude and direction precluded the possibility of ‘‘memorizing’’ the required limb trajectories. In order to direct the motion of the swing foot appropriately, it was necessary for the CNS to combine on-line sensory feedback about the perturbation-induced body motion with the ‘‘remembered’’ visual support-surface information. This information is presumably ‘‘remembered’’ within the framework of an egocentric visual map, formed by combining retinotopic information with extra-retinal cues pertaining to the orientation of the eyes with respect to the head (Colby 1998). We have proposed that the CNS automatically formulates such a map in daily life, as a contingency in the event that rapid reaction to loss of balance is suddenly required (Ghafouri et al. 2004). This egocentric mapping may occur in parallel with the allocentric mapping that guides navigational behaviour (Colby 1998). Ongoing work, involving intermittent and unpredictable motion of multiple obstacles, is examining factors that affect how frequently the postulated egocentric map is updated and how long the map can be ‘‘remembered’’ without being updated.

Conclusions

Visual fixation of the foot or floor was not essential for accurate control of the foot movement during the execution of rapid, perturbation-evoked stepping reactions, nor was the apparent switching of attention that followed perturbation onset linked, in any consistent way, to overt changes in visual fixation. Spatial features of the support surface were apparently ‘‘remembered’’ prior to perturbation onset and used to help plan or guide the foot trajectory and step placement, thereby allowing both vision and attention to be directed to other demands during the execution of the balance reaction.

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