Does the “eyes lead the hand” principle apply to reach-to-grasp movements evoked by unexpected balance perturbations?

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\textbf{A B S T R A C T}

A fundamental principle that has emerged from studies of natural gaze behavior is that goal-directed arm movements are typically guided by a saccade to the target. In this study, we evaluated a hypothesis that this principle does not apply to rapid reach-to-grasp movements evoked by sudden unexpected balance perturbations. These perturbations involved forward translation of a large (2 \times 6 m) motion platform configured to simulate a “real-life” environment. Subjects performed a common “daily-life” visuo-cognitive task (find a telephone and make a call) that required walking to the end of the platform, which was triggered to move as they approached a handrail mounted alongside the travel path. A deception was used to ensure that the perturbation was truly unexpected. Eleven of 18 healthy young-adult subjects (age 22–30) reached to grasp or touch the rail in response to the balance perturbation. In support of the hypothesis, none of these arm reactions was guided by concurrent visual fixation of the handrail. Seven of the 11 looked at the rail upon first entering the environment, and hence may have used “stored” central-field information about the handrail location to guide the subsequent arm reaction. However, the other four subjects never looked directly at the rail,
indicating a complete reliance on peripheral vision. These findings add to previous evidence of distinctions in the CNS control of volitional and perturbation-evoked arm movements. Future studies will determine whether similar visuo-motor behavior occurs when the available handhold is smaller or when subjects are not engaged in a concurrent visuo-cognitive task.

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1. Introduction

A fundamental principle that has emerged from studies of natural (unconstrained) gaze behavior is that “the eyes lead the hand” during volitional goal-directed arm movements. This is typically the case whether the arm movement is performed as an isolated aim, point, reach or reach-to-grasp task or occurs within the context of a more complex daily-life activity, and appears to apply for both rapid and preferred-speed movements (Abrams, 1992; Abrams, Meyer, & Kornblum, 1990; Carnahan & Marteniuk, 1991; Desmurget, Pelisson, Rossetti, & Prablanc, 1998; Haycoe & Ballard, 2005; Land, 2006; Prablanc, Echallier, Komilis, & Jeannerod, 1979; Sivak & MacKenzie, 1992).

Typically, a saccade to the target is initiated prior to the start of the limb movement, although the limb may sometimes start to move first (Abrams, 1992). Nonetheless, because the saccade is much faster than the limb movement, visual fixation of the target almost always occurs well before the hand reaches the target (Abrams, 1992; Carnahan & Marteniuk, 1991). This gaze behavior facilitates control of the limb movement in two ways, by providing: (1) high-acuity retinal information about the location and characteristics of the target, as well as the relative position of hand and target during the final stages of the movement (Abrams, 1992); and (2) extra-retinal (oculomotor) information about the eye orientation and saccade amplitude that can also contribute to the programming of the limb movement (Enright, 1995; van Donkelaar, 1998).

Although it seems clear that “the eyes lead the hand” principle applies to a wide range of volitional motor behavior, the extent to which it governs the control of rapid reach-to-grasp movements evoked by sudden unexpected balance perturbation has not been established. These perturbation-evoked reactions are a prevalent response to sudden loss of balance, and can play an important role in preventing falls (Bateni, Zecevic, McIlroy, & Maki, 2004; Maki & McIlroy, 1997, 2005; Maki, Perry, & McIlroy, 1998; McIlroy & Maki, 1999b). The kinematic and electromyographic features of these arm reactions are similar, in many respects, to volitional reaction-time reach-to-grasp movements elicited by a visual cue; however, the perturbation-evoked movements are typically initiated and executed much more rapidly than the fastest efforts to move the arm volitionally (Gage, Zabjek, Hill, & McIlroy, 2007; Maki & McIlroy, 1997). For example, one balance-perturbation study reported a mean deltoid activation latency of 137 ms, in comparison to 239 ms for reactions elicited by a visual cue (subjects instructed to grasp a handrail as quickly as possible) (Gage et al., 2007), and other studies have reported mean perturbation-trial latencies as short as 90 ms (McIlroy & Maki, 1995b). These latencies are very similar to the timing of the earliest lower-limb muscle activation (typically, 90–140 ms at the ankle) that is evoked by balance perturbation [for reviews, see Dietz (1992); Horak & MacPherson (1996); Maki & McIlroy (2005)].

The urgent need to respond rapidly in order to maintain balance and prevent falling imposes temporal constraints that could possibly preclude the use of eye movements to guide the initial trajectory of perturbation-evoked reach-to-grasp movements. Typically, the time required to initiate a saccade is about 200 ms (Trottier & Pratt, 2005) or longer (e.g., 300–500 ms (Carnahan & Marteniuk, 1991)); however, this can be reduced to 90–120 ms when there is a temporal gap between the offset of the initial fixation object and the onset of the peripheral target (Bekkering, Pratt, & Abrams, 1996; Fischer & Ramsperger, 1984; Fischer & Weber, 1993; Trottier & Pratt, 2005). Although it is unclear whether these “express” or “gap-effect” saccades occur during natural behavior, it can be safely assumed that saccade initiation will require at least 90 ms, and that the execution of the eye movement will require an additional 40–70 ms (Pratt, Dodd, & Welsh, 2006). Furthermore, the need to scan the environment
to identify a suitable object to grasp could require multiple saccades, and the time required to process
the visual information, after each saccade, would add further delays of 50 ms or more per saccade
(Findlay, Brown, & Gilchrist, 2001). These temporal considerations have led to the suggestion that
the central nervous system (CNS) may avoid the need to execute such saccades “online” (i.e., after per-
turbation onset) by instead utilizing visuo-spatial information (VSI) that is either stored in memory or
acquired online from the peripheral visual field (Ghafouri, McIlroy, & Maki, 2004). However, to our
knowledge, the natural (unconstrained) gaze behavior that actually occurs in reacting to an unex-
pected balance perturbation has not yet been studied.

The present study is the first in a planned series of studies aimed at understanding the visual con-
trol of rapid reach-to-grasp reactions evoked under conditions designed to simulate “real-life” loss-of-
balance situations, where the perturbation typically occurs suddenly and unexpectedly. In these
experiments, the perturbations are delivered via forward translation of a large motion platform on
which the subjects ambulate, and are triggered during the single-support phase of the gait cycle so
as to create a slip-like perturbation. To simulate a “real-life” situation, the platform is configured to
resemble a visually-complex office environment, and subjects are asked to perform a typical task of
daily life that requires walking to the end of the platform. The platform translation is triggered to oc-
cur as the subject walks alongside a handrail mounted on the platform, and a deception is employed to
ensure that the perturbation is truly unexpected. Analysis is restricted to one trial per subject – the
subject’s first exposure to the environment and perturbation. Although this single-trial approach se-
verely limits the quantity of data that can be collected, it is essential in order to avoid the adaptations
that can occur when multiple trials are performed (Maki & Whitelaw, 1993; McIlroy & Maki, 1995a;
Oude Nijhuis et al., 2009) or subjects know in advance that they may experience a balance perturba-
tion (Pavol, Runtz, & Pai, 2004).

The specific purpose of this initial study was to determine whether there is any evidence that the
“eyes lead the hand” principle applies to rapid reach-to-grasp reactions evoked by unexpected balance
perturbations, in healthy young adults. We hypothesized that this principle would not apply, i.e.,
reach-to-grasp reactions would not be guided by a concurrent saccade to the handrail. Instead, we ex-
pected that the CNS would utilize stored VSI to guide the arm motion, acquired and stored upon enter-
ing the unfamiliar environment via natural exploratory gaze behavior (i.e., one or more saccades to the
rail). A new methodology, developed by the authors (Scovil, King, & Maki, 2009), was used in process-
ing the gaze data in order to quantify the extent to which the rail was visible within the central and
peripheral visual fields. A subset of the present data was included in a separate study addressing age-
related changes in gaze behavior (King et al., 2009).

2. Methods

2.1. Participants

The study involved 10 male and eight female healthy young adults, with a mean age of 25 years
(range 22–30), mean height of 173 cm (range 154–189 cm) and mean body mass of 73 kg (range
48–127 kg). All participants were naïve to the specific purpose of the study, and had not participated
in any previous balance studies. All were right-handed, had a minimum corrected Snellen visual acuity
of 20/40, and reported no neurological, sensory or musculoskeletal deficits. Each subject provided
written informed consent, in compliance with the ethical approval granted by the institutional ethics
review board.

2.2. Protocol

A large computer-controlled motor-driven motion platform (2 × 6 m) was set up to simulate a
“real-life” office environment, including a stair, handrail, desk and telephone, plus various visual
distracters (Fig. 1a and b). A wall and door prevented the subject from viewing the environment prior
to the start of the trial. A standardized script informed the subjects that there was a room behind the
door, with an office area located at the far end of the room, and instructed them to open the door, enter
the room, walk to the end at a normal pace and make a telephone call. This task thus required
performing a visual search for the telephone while walking to the end of the platform. For safety, all subjects wore a harness attached to a low-friction overhead track that moved smoothly and did not impede the subject's movements.

The handrail and stair were mounted near the middle of the platform (near-end of rail 1.8 m from doorway, 1.5 m in front of stair riser). Sudden forward translation of the platform (square-wave acceleration/deceleration profile: amplitude 3.5 m/s², peak velocity 1.1 m/s, displacement 0.43 m, duration 0.6 s) was triggered to occur when the subject stepped on a pressure-sensitive mat adjacent to the handrail, thereby inducing a backward falling motion (similar to the effect of a slip). Objects mounted on the platform forced subjects to walk within a relatively narrow corridor (0.74 m wide) when approaching the stair, and thereby ensured that the handrail was well within reach when the perturbation was delivered. The rail was cylindrical, with a diameter (38 mm) and height (0.88 m above leading edge of stair tread) previously shown to allow effective grasping by persons encompassing a wide range of body heights and hand sizes (Maki, Perry, Scovil, Mihailidis, & Fernie, 2006).

To avoid confounding effects of learning and adaptation, analysis was restricted to one trial per subject, which was the subject’s first exposure to the platform motion and to the simulated office environment. A deception was used to ensure that the perturbation was truly unexpected: subjects were told that the first trial was a “practice trial” to help them become accustomed to the testing procedure and that the platform would not move during this trial. The effectiveness of the deception was confirmed by querying the subjects after the trial, at which point the reason for the deception was explained.

Subjects were given no instructions regarding their gaze behavior.

2.3. Data collection and analysis

A lightweight head-mounted eye tracker (Model 501, Applied Sciences Laboratories, Bedford, MA, USA) was used to record eye movements (horizontal and vertical) at a sampling rate of 60 Hz. The
tracker uses an infrared light source to produce a corneal reflection, which is detected, along with an image of the pupil, by a miniature video camera, and the separation between the corneal reflection and pupil is used to compute the angle of the line-of-gaze relative to the head. This is then used to determine the point-of-gaze location in relation to the video images recorded (at 60 Hz) by a miniature forward-facing “scene camera” (also mounted rigidly on the head), and the point-of-gaze is displayed as a cursor on these video images. Effects of camera-lens distortion and other non-linearities are corrected by performing a calibration prior to the start of the experiment (ASL, 2000).

Custom-designed software (Scovil et al., 2009) was used to augment these point-of-gaze data by superimposing “gaze ellipses” (corresponding to visual angles of 5°, 10°, 15°, 20°, 30° and 40°, in relation to the point-of-gaze) on each frame of the scene-camera video (Fig. 1c). These images were used to determine whether visual fixation of the handrail occurred, as well as the onset time and duration of each such fixation or near-fixation. A fixation was defined to occur if the eye-tracker images showed that the point-of-gaze was stable (within ±2°) for ≥100 ms, as per previous studies (Chapman & Hollands, 2010; Hollands, Patla, & Vickers, 2002; King et al., 2009; Panchuk & Vickers, 2006, 2009; Patla & Vickers, 1997, 2003; Vickers, 1996; Vickers & Williams, 2007). Handrail fixation was defined to occur if the fixation point-of-gaze was within 5° of some portion of the handrail. For all other fixations, we characterized the proximity of the point-of-gaze to the rail in terms of the nearest gaze-ellipse annulus (5–10°, 10–15°, 15–20°, 20–30° or >30°) that overlapped with some portion of the rail.

A three-dimensional video-based motion-analysis system (Vicon-Peak Performance, Oxford, UK) was used to characterize gross motor behaviors (opening of the hand aperture, grasping or touching the rail, overt reaching errors, compensatory step reactions, falls into the safety harness) and to determine: (1) time of initial rail contact; (2) time of grasp completion (all fingers wrapped around rail); (3) the trajectory of the reaching motion; and (4) turning of the head toward the rail. The system comprised four cameras that provided a calibrated viewing volume (~2 m high, 2 m wide, 3 m long), centered near the near-end of the handrail. Coordinates of reflective markers placed bilaterally on the wrist (radial styloid), shoulder (acromion) and head (temples), as well as on the handrail, were digitized (60 Hz) and low-pass filtered (6 Hz cut-off).

The kinematic features of the arm reactions were characterized in terms of the motion of each wrist marker in relation to the ipsilateral shoulder marker. Motion of the right wrist marker in relation to the handrail markers was also used to characterize reaching responses. Transverse-plane head rotation (yaw), relative to the rail, was based on the angle of the line segment connecting markers on the left and right temples. Overt motor errors were defined to occur if there was a collision between the back of the hand and the handrail, or if the hand overshot the rail. Identification of hand-aperture opening was facilitated by reflective tape placed on the nail of the thumb and index finger. Arm-reaction onset-timing was derived from surface electromyographic (EMG) recordings from the right medial deltoid and biceps brachii (band-pass filtered, 10–500 Hz; sampled at 1000 Hz). EMG onset was determined by a computer algorithm (McIlroy & Maki, 1993) and confirmed by visual inspection. All EMG, kinematic and gaze timing values were defined relative to perturbation onset (PO) as recorded by an accelerometer (PO = platform acceleration >0.1 m/s²).

3. Results

The main features of the arm reactions and associated gaze behavior are summarized in Table 1. Recorded data (yaw eye rotation relative to the head, yaw rotation of the head, lateral wrist displacement relative to the handrail, medial-deltoid EMG) for example trials are plotted in Fig. 2, along with eye-tracker video images showing the point-of-gaze at the onset of each new visual fixation. Key kinematic features of the arm movements are summarized in Fig. 3, and example left and right arm trajectories (wrist relative to shoulder) are plotted in Fig. 4. The timing of all visual fixations of the handrail (within a visual angle of 5°) is displayed, for each of the subjects, in Fig. 5). The eye- and head-angle plots in Fig. 2 are provided to illustrate the relative contributions of both eye and head rotations in achieving visual fixations; however, it is important to note that the fixations were also influenced by ongoing translation of the trunk and head. It is for this reason that stable fixations were defined on the basis of the eye-tracker video images, as detailed earlier in Section 2.3.
## Table 1
Summary of the perturbation-evoked arm reactions and associated gaze behavior [central fixations of the handrail (i.e., rail within 5° of the point-of-gaze) are highlighted in bold text].

<table>
<thead>
<tr>
<th>Subject</th>
<th>Arm reactions</th>
<th>Gaze fixations ( ^a )</th>
<th>Timing (ms) ( ^b )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overt error</td>
<td>Prior to perturbation onset ( ^c )</td>
<td>At perturbation onset</td>
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<td></td>
<td></td>
<td>Point of gaze</td>
<td>Visual angle to rail</td>
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<tr>
<td><strong>Grasp of rail (prehension)</strong></td>
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<tr>
<td>S1</td>
<td>–</td>
<td>Phone</td>
<td>10–15°</td>
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<td>S2</td>
<td>–</td>
<td>Chair</td>
<td>15–20°</td>
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<tr>
<td>S3</td>
<td>–</td>
<td>Post</td>
<td>0–5°</td>
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<tr>
<td>S4</td>
<td>–</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td>S5</td>
<td>Collision</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td>S6</td>
<td>Over-shoot</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td><strong>Touch of rail (but no prehension)</strong></td>
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<td>S7</td>
<td>–</td>
<td>Phone</td>
<td>5–10°</td>
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<td>S8</td>
<td>–</td>
<td>Floor</td>
<td>5–10°</td>
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<td>S9</td>
<td>–</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td>S10</td>
<td>Over-shoot</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td>S11</td>
<td>Over-shoot</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td><strong>Reach toward rail (but no rail contact)</strong></td>
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<tr>
<td>S12</td>
<td>–</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td>S13</td>
<td>–</td>
<td>Post</td>
<td>0–5°</td>
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<tr>
<td>S14</td>
<td>–</td>
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<tr>
<td><strong>No overt reach toward rail</strong></td>
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<tr>
<td>S15</td>
<td>–</td>
<td>Rail</td>
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<td>S16</td>
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<tr>
<td>S17</td>
<td>–</td>
<td>Rail</td>
<td>0–5°</td>
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<tr>
<td>S18</td>
<td>–</td>
<td>Stair</td>
<td>20–30°</td>
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</tbody>
</table>

\( ^a \) See Fig. 1b for a photograph showing the location of the various fixation targets noted in the table ("post" indicates the vertical post supporting the far end of the handrail; "monitor" indicates the computer monitor located on the desk).

\( ^b \) All timing values are in relation to perturbation onset (time = 0.0); negative values indicate events occurring prior to perturbation onset.

\( ^c \) For the pre-perturbation fixations, the listed gaze data correspond to the nearest fixation (smallest visual angle) with respect to the handrail.

\( ^d \) For the fixations occurring after perturbation onset, only fixations beginning prior to touch or grasp completion are listed, in grasp/touch trials. For the other trials, all fixations beginning within 1 s of perturbation onset are listed.

\( ^e \) No stable fixation.

\( ^f \) Data not available due to technical problems.
As detailed in Table 1, 11 of the 18 subjects grasped \((N = 6)\) or touched \((N = 5)\) the handrail with the right hand in reaction to the platform perturbation. Although all 11 ultimately grasped or touched the rail successfully, four made overt errors during the reaching motion. In one case, the back of the hand collided with the rail, and overshoot error (and subsequent reversal in wrist trajectory) was evident in three cases (e.g., see wrist displacement plot in Fig. 2b). Of the seven subjects who did not grasp or touch the rail, three appeared to initiate a reach-to-grasp reaction (as evidenced by lateral displacement of the right hand toward the rail and opening
of the right-hand aperture; Fig. 4c) but did not contact the rail. The remaining four subjects moved both hands laterally but did not appear to reach for the rail, as evidenced by the absence of

### Key kinematic features of the arm reactions:

(A) position and velocity of each arm at time of perturbation onset (PO); (B) maximum displacement and velocity of each arm during the response to the perturbation. Grey and black bars correspond to the left and right arms, respectively. The displayed data represent the motion of the wrist marker relative to the ipsilateral shoulder marker. The data in B represent the maximum values that occurred along the antero-posterior, medio-lateral and vertical axes during the initial arm movement evoked by the perturbation (i.e., prior to any reversal in direction), within 1.0 s of PO. Positive values (to the right of the vertical zero-line) indicate motion in the forward, lateral or upward direction; zero displacement indicates a position where the wrist marker is directly below the shoulder marker, with the arm fully extended. To facilitate comparison between subjects, displacements and velocities are scaled as a percentage of subject height, as per the indicated scaling bars (note the different scaling in A and B). The numerical values listed to the left of each bar, in B, indicate the time (in ms) at which the maximum displacement or velocity occurred, relative to time of PO.

### Fig. 3

<table>
<thead>
<tr>
<th></th>
<th>Forward</th>
<th>Lateral</th>
<th>Upward</th>
<th>Forward</th>
<th>Lateral</th>
<th>Upward</th>
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<tr>
<td><strong>Grasp without error</strong></td>
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<td>S1</td>
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<td><strong>Grasp with error</strong></td>
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<td><strong>Touch without error</strong></td>
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<td>S7</td>
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<td><strong>Touch with error</strong></td>
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<tr>
<td><strong>Reach toward rail</strong></td>
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- 10% of body height
- 25% of body height per second
right-hand-aperture opening (Figs. 3b and 4b). They did, however, raise both arms forward, consistent with a “counterbalancing” reaction that generates stabilizing reaction force/moment at the shoulders (Hoff, 2007). Additional stabilization was apparently provided via compensatory stepping, i.e., overt changes in the direction and/or step-length of the ongoing step (in progress at PO) and/or subsequent steps (Maki & McIlroy, 1997). All subjects took one or more compensatory steps (regardless of whether they used the handrail), and none fell or relied on the safety harness to prevent falling.

Typically, in both reach and non-reach trials, both arms tended to move forward, upward and laterally subsequent to PO; however, this was not always the case (e.g., small backward left-arm motion in subject S1, negligible vertical left-arm motion in S7; see Fig. 3b). In addition, there was considerable variation in the spatial and temporal features of the arm movements (Figs. 3b and 4). It seems likely...

**Fig. 3 (continued)**
Fig. 4. Example right (solid line) and left (broken line) arm trajectories for trials involving: (A) a reach-to-grasp reaction (subject S4), and (B) a reaction that did not appear to involve reaching for the rail (subject S16) and (C) an apparent reach reaction that did not result in handrail contact (subject S14). Each plot shows the displacement of the wrist marker in relation to the ipsilateral shoulder marker. Upward displacements on the graphs indicate forward, rightward or upward wrist motion. The vertical lines indicate time of perturbation onset (PO), time of initial rail contact (IC), time of grasp completion (GC), and the time corresponding to the displayed video images (VI). Each plot displays 1.1 s of data (0.1 s prior to PO, 1.0 s after PO). The accompanying video images display the arm displacement at time of maximum lateral right-wrist displacement, and illustrate the opening of the hand aperture that occurred during reach reactions (A and C) and the absence of aperture opening that appears to indicate the absence of an effort to reach for the rail (B) [white circles have been drawn to highlight the location of reflective tape placed on the nail of the right thumb and index finger].
that at least some of the variation may have been a consequence of the variability in the position and velocity of the arms at time of PO (Fig. 3a).

The tabulated and plotted gaze data (Table 1; Figs. 2 and 5) clearly show that the arm movements were not guided by concurrent visual fixation of the handrail. First, there was no evidence that any of the 11 subjects who grasped or touched the handrail were looking at the rail at time of perturbation onset (PO). Each darkened portion of each bar represents an interval during which gaze was fixated on the handrail (within a visual angle of 5°). The grey vertical line segments in the bars indicate the time at which initial contact with the rail occurred, in grasp and touch trials. In addition, for grasp trials, the black vertical line segments indicate the time at which the grasp was completed (fingers fully wrapped around the rail). Note that none of the subjects fixated on the handrail during the interval between PO and contact with the rail. Eleven subjects fixated on the rail one or more times prior to PO, while five subjects (four of whom grasped or touched the rail) never fixated on the rail at any time (before or after PO). Note: due to technical problems, S3 had no gaze data prior to the pre-PO fixation marked with the *, S18 had no gaze data during the post-PO interval, and S14 had no gaze data for the entire trial.

Fig. 5. Visual fixation of the handrail displayed as a function of time, for each of the subjects. Time-zero corresponds to the onset of the balance perturbation (platform acceleration >0.1 m/s²); negative and positive time values (in s) correspond to events occurring before and after perturbation onset (PO), respectively. Each darkened portion of each bar represents an interval during which gaze was fixated on the handrail (within a visual angle of 5°). The grey vertical line segments superimposed on the bars indicate the time at which initial contact with the rail occurred, in grasp and touch trials. In addition, for grasp trials, the black vertical line segments indicate the time at which the grasp was completed (fingers fully wrapped around the rail). Note that none of the subjects fixated on the handrail during the interval between PO and contact with the rail. Eleven subjects fixated on the rail one or more times prior to PO, while five subjects (four of whom grasped or touched the rail) never fixated on the rail at any time (before or after PO). Note: due to technical problems, S3 had no gaze data prior to the pre-PO fixation marked with the *, S18 had no gaze data during the post-PO interval, and S14 had no gaze data for the entire trial.
The closest (most central) post-PO rail fixations occurred in the two subjects who made post-PO fixations of the handrail post (subjects S6 and S10, in Table 1). These fixations brought a portion of the rail within the central 10° of the visual field; however, they began well after the initiation of the arm reaction (>125 ms after the earliest arm–muscle activation). In both cases, the timing of these relatively late fixations appeared to be more closely associated with an overshoot error and the subsequent corrective reversal in the wrist trajectory (e.g., Fig. 2b).

Although there was no evidence of the “eyes leading the hand” during the execution of the arm reaction, 7 of the 11 subjects who used the handrail did fixate on it (within a visual angle of 5°) one or more times after opening the door and entering the test environment, prior to PO. Hence, “stored” central-field information about the handrail was potentially available to aid in programming the perturbation-evoked arm reaction. The other four subjects (S1, S2, S7 and S8 in Table 1) never looked directly at the rail at any time prior to rail contact (before or after PO), yet grasped or touched the rail without overt error (e.g., Fig. 2a). The fact that the rail was never brought within the central 5° of the visual field indicates that these four subjects relied entirely on more peripheral regions of the visual field to locate the rail.

The seven subjects who did not contact the rail showed no obvious differences in gaze behavior, in comparison to the 11 subjects who grasped or touched the rail. Gaze data were missing or incomplete for two of these seven subjects (due to technical problems); however, none of the remaining subjects fixated on the rail at or after PO. Conversely, all but one did fixate on the rail (within 5°) one or more times prior to PO.

4. Discussion

The results of the study clearly support the hypothesis that reach-to-grasp reactions evoked by unexpected balance perturbation would not be guided by a concurrent visual fixation of the handrail. Indeed, none of the 11 subjects who grasped or touched the handrail in reaction to the perturbation executed a saccade to the rail in conjunction with the initiation of the reaching movement, and none were looking at the rail at time of perturbation onset (PO). There were no cases where a post-perturbation fixation brought the rail within the central 5° of the visual field, and only two cases where the visual angle to any portion of the rail was within 10°. The latter two fixations both began well after the initiation of the arm reaction, and appeared to be associated with the correction of an overshoot error. These findings demonstrate gaze behavior that is distinctly different from that observed during studies of unconstrained volitional goal-directed arm movements, and suggest that the “eyes lead the hand” principle that typically governs such volitional movements may not apply to compensatory arm movements evoked by unexpected loss of balance in typical daily-life situations and environments.

As detailed in Section 1, the differing visual control strategies used in compensatory and volitional arm movements may arise as a consequence of the temporal constraints that govern perturbation reactions, i.e., the need to react very rapidly in order to prevent a fall. Another possibility is that the gaze behavior observed during the perturbation reactions was influenced by other task demands, such as the need to avoid tripping over objects in the course of recovering equilibrium. The reach-to-grasp reactions were always accompanied by compensatory stepping reactions, during which it has been shown that gaze is sometimes redirected downward toward the floor (Zettel, Holbeche, McIlroy, & Maki, 2005; Zettel, McIlroy, & Maki, 2008; Zettel, Scovil, McIlroy, & Maki, 2007). However, in the present study, gaze was redirected toward the floor or stair, subsequent to PO, in only 3 of the 11 trials that involved grasping or touching of the rail. More frequently (8 of 11 cases), subjects maintained or redirected gaze at objects related to the telephone task (i.e., the desk or objects mounted on the desk). This is consistent with previous findings that subjects are much less likely to look downward during stepping reactions when engaged in an ongoing visuo-cognitive task (Zettel et al., 2008). Potentially, failure to disengage attention from the telephone task in the present study could have also had an analogous effect in inhibiting redirection of gaze toward the handrail. Further work is needed to determine whether, in fact, subjects are more likely to look at the handrail during the perturbation-evoked reaction when there is no concurrent visuo-cognitive task.
The finding that online central-field fixation of the handrail did not occur implies that initial arm movement was instead guided using: (1) online VSI from the peripheral field, and/or (2) VSI acquired and stored during pre-PO fixations that captured the rail either centrally or peripherally. Although most subjects did fixate centrally on the rail one or more times prior to PO, the fact that four subjects grasped or touched the rail without ever fixating on it suggests that peripheral vision may play an important role in guiding these balance-recovery reactions, and adds to the balance literature indicating that peripheral vision can also contribute significantly to stabilizing the head and/or body (Bardy, Warren, & Kay, 1999; Berencsi, Ishihara, & Imanaka, 2005; Schmid, Casasbienca, Bottaro, & Schieppati, 2008). Studies of volitional reaching or pointing arm movements would indicate that the reliance on either stored target information (Heath & Binsted, 2007; Jackson, Jackson, & Rosicky, 1995; Kopinska & Harris, 2003; Lemay & Stelmach, 2005) or peripheral vision (Bock, 1986, 1993; Henriques & Crawford, 2002; Henriques, Klier, Smith, Lowy, & Crawford, 1998; Lewald & Ehrenstein, 2000) will reduce the accuracy of the end-point control. Although the length of the handrail used in the present study allowed considerable leeway for error in terms of antero-posterior hand placement, the narrow width of the handrail presented demands for lateral reach accuracy that are comparable to many previous volitional-reach studies, and the high frequency of reaching errors (4 of 11 trials) speaks to the challenge of these accuracy demands. Further studies are needed to determine whether the gaze behavior associated with perturbation-evoked reactions is affected by the dimensions of the objects that are available to touch or grasp for support.

The pre- and post-PO gaze behavior of the seven subjects who did not use the handrail to aid in balance recovery appeared to be very similar to that of the 11 subjects who grasped or touched the rail. It is not clear why these seven did not use the rail to aid in balance recovery. The data provide no compelling evidence to suggest that a failure to “notice” the rail or to map its location was a factor, as there was only one case where the subject did not fixate on the rail prior to PO. For the three subjects who appeared to initiate a reach, undershoot error is a possible explanation for the failure to contact the rail, however, one would expect such error to be followed by attempts to correct the arm trajectory, and we observed no overt evidence of such corrective efforts. Rather, it appears more likely that these were aborted reach-to-grasp reactions, in which the reaction is initiated rapidly to safeguard against falling but is subsequently aborted (McIlroy & Maki, 1995b).

The present results were based on a 100-ms criterion for gaze fixation. This criterion has been commonly used in gaze-behavior studies (see citations in Section 2.3), is based on minimum fixation durations observed during such studies (see Vickers, 1996), and presumably reflects the minimum time needed to acquire and process the required VSI. To examine the effect of using this fixation criterion, we repeated the analyses using a 50-ms criterion. Fixation times as short as 50 ms occur rarely during visual-search tasks, even when subjects are well practised and search rapidly for a well-defined and highly-visible target (Findlay et al., 2001); therefore, it seems unlikely that fixation times as short as this would suffice in the present study, where the visual environment was unfamiliar and complex. However, even when using the 50-ms criterion, the main results were largely unchanged: 10 of 11 handrail users continued to exhibit no evidence of central-field (0–5°) handrail fixation after PO (the remaining subject, S9, exhibited a 67 ms fixation that began 135 ms after the onset of the arm reaction), and all four subjects who were previously inferred to rely entirely on peripheral vision continued to show no rail fixations either before or after PO.

The present study is subject to a number of limitations. First, the single-trial/deception paradigm that was used to prevent adaptation limited the study to a relatively small set of observations. Although the current sample was sufficient to provide statistical support for our central hypothesis, it is clear that larger numbers of subjects will need to be tested in order to obtain reliable estimates of the incidence rate for specific observed behaviors, e.g., reaches that are guided entirely by peripheral vision. Another limitation is that our focus on natural behavior allowed wide variation in visual inputs (e.g., timing and duration of central-field rail fixation) and limited control over kinematic variables such as gait speed, posture and position/motion of the body/limbs in relation to the handrail at PO. Thus, although the current approach is valuable in revealing natural behavior, there is a need for complementary studies that probe the control mechanisms and mediating factors by manipulating and/or controlling specific visual and kinematic variables. For example, partially-occluded contact lenses can be used to force reliance on peripheral or central vision (Sivak & MacKenzie, 1990,
and liquid-crystal goggles can force reliance on stored or online VSI (Cheng, McKay, King, & Maki, 2009; Scovil, Zettel, & Maki, 2008). Control over initial kinematic conditions can be achieved by applying perturbations to stationary subjects, while using motor-driven devices to introduce well-controlled variation in the location of surrounding obstacles or handholds (Cheng et al., 2009; Scovil et al., 2008; Zettel et al., 2007).

5. Conclusion

The results presented here demonstrate that the initiation of reach-to-grasp reactions evoked by unexpected balance perturbation was not guided by concurrent central-field visual fixation of the grasp target. Hence, one must conclude that the initial arm movement was instead guided using stored central-field VSI, stored peripheral-field VSI and/or online peripheral-field VSI, and further work is needed to determine the degree to which these alternate sources of VSI are necessary or sufficient. Although the “eyes lead the hand” principle that has emerged from studies of volitional arm movements clearly did not govern the reactions evoked in the present study, it remains to be determined whether this principle applies when the target handhold is smaller or when there is no concurrent visuo-cognitive task. Nonetheless, the present findings add to the literature indicating possible distinctions in the CNS control of volitional and compensatory arm movements, and point to the importance of considering these distinctions during the clinical assessment and treatment of movement and balance deficits.

Acknowledgments

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References


