The use of peripheral vision to guide perturbation-evoked reach-to-grasp balance-recovery reactions

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Abstract

For a reach-to-grasp reaction to prevent a fall, it must be executed very rapidly, but with sufficient accuracy to achieve a functional grip. Recent findings suggest that the CNS may avoid potential time delays associated with saccade-guided arm movements by instead relying on peripheral vision (PV). However, studies of volitional arm movements have shown that reaching is slower and/or less accurate when guided by PV, rather than central vision (CV). The present study investigated how the CNS resolves speed-accuracy trade-offs when forced to use PV to guide perturbation-evoked reach-to-grasp balance-recovery reactions. These reactions were evoked, in 12 healthy young adults, via sudden unpredictable anteroposterior platform translation (barriers deterred stepping reactions). In PV trials, subjects were required to look straight-ahead at a visual target while a small cylindrical handhold (length 25% > hand-width) moved intermittently and unpredictably along a transverse axis before stopping at a visual angle of 20°, 30°, or 40°. The perturbation was then delivered after a random delay. In CV trials, subjects fixated on the handhold throughout the trial. A concurrent visuo-cognitive task was performed in 50% of PV trials but had little impact on reach-to-grasp timing or accuracy. Forced reliance on PV did not significantly affect response initiation times, but did lead to longer movement times, longer time-after-peak-velocity and less direct trajectories (compared to CV trials) at the larger visual angles. Despite these effects, forced reliance on PV did not compromise ability to achieve a functional grasp and recover equilibrium, for the moderately large perturbations and healthy young adults tested in this initial study.

Keywords

Arm movement; Balance reactions; Grasp; Peripheral vision; Postural balance; Reach

Introduction

Historically, studies of balance-recovery reactions have tended to focus primarily on the lower limbs; however, there is an increasing awareness that rapid movements of the upper limbs also play an important role in stabilizing the body, both in daily life (Maki and McIlroy 1996, 1997; Rabinovitch et al. 2009) and in experimental settings (Romick-Allen and Schultz 1988; McIlroy and Maki 1995b; Maki and McIlroy 1997; Tang et al. 1998; Allum et al. 2002; Marigold and Patla 2002; Marigold et al. 2003; Misiaszek 2003; Cham and Sandrian 2007; Roos et al. 2008; Pijnappels et al. 2010). In the event that attempts to recover balance are unsuccessful, arm reactions may also act to help absorb the energy of the fall and protect against head injury (Roberts 1978) or hip fracture (Feldman and Robinovitch 2007).

Even small balance perturbations can evoke arm reactions, particularly when the perturbation is novel or unexpected (Maki and Whitelaw 1993; Corbeil et al. 2004), and it has been proposed that the arm movements can help to stabilize the body through various 'counter-balancing' inertial or gravitational mechanisms (Romick-Allen and Schultz 1988; Allum et al. 2002; Marigold and Patla 2002; Marigold et al. 2003; Misiaszek 2003; Hoff 2007; Marigold and Misiaszek 2009; Roos et al. 2008; Pijnappels et al. 2010).

Alternatively, if a handrail or other stable object is available, then the stabilizing arm reaction very commonly involves reaching to touch or grasp the object for support (McIlroy and Maki 1995b; Maki and McIlroy 1997; Bateni et al. 2004; King et al. 2009; King et al. in press), and such reactions have the potential to provide a far greater degree of stabilization than counter-balancing arm movements (Maki et al. 2003). However, the visual demands of controlling these 'compensatory' reach-to-grasp reactions are high: it is necessary to identify and locate a suitable handhold, guide an appropriately directed reach toward it, and grasp it, all while compensating for ongoing motion of the torso and head (Ghafouri et al. 2004). Furthermore, the urgent need to react rapidly in order to prevent a fall from occurring can impose temporal constraints that may severely limit the capacity to acquire and process the needed visuospatial information (Maki and McIlroy 2005).

One potential strategy for dealing with these temporal constraints is to use peripheral vision to guide the reaching motion, thereby eliminating the delays that could occur if instead it were necessary to execute one or more saccades in order to guide the hand toward a suitable handhold. The use of peripheral vision is supported by initial results from two recent studies (King et al. 2009; King et al. in press) of natural balance-recovery behavior elicited by unexpected perturbation as subjects walked through an unfamiliar environment. Four of eleven young adults and seven of ten older subjects who used a handrail to recover balance grasped or touched the rail without visually fixating on it at any time, either before or after perturbation onset. All four young adults performed the reach without overt error; however, the hand either overshot or collided with the rail in four of the seven older subjects.

Although this small sample does not allow definitive conclusions to be drawn, the results do suggest that peripheral vision can often be an adequate source of spatial information for guiding functionally effective reach-to-grasp reactions, particularly in healthy young adults.

Although no studies have systematically examined the role of peripheral vision in the control of perturbation-evoked reaching reactions, studies of volitional pointing, aiming, reaching, and grasping movements have indicated that such movements can be guided using peripheral vision alone. However, the movements are invariably more accurate when central vision of the target is allowed, as forced reliance on peripheral vision leads to increased variability, as well as systematic errors (e.g. undershoot in reach amplitude) (Bock 1986; Sivak and MacKenzie 1990; Bock 1993; Henriques et al. 1998; Lewald and Ehrenstein 2000; Henriques and Crawford 2002; Schlicht and Schrater 2007) and adaptive changes in strategy (e.g. increase in grasp aperture) (Sivak and MacKenzie 1990; Goodale and Murphy 1997; Brown et al. 2005; Schlicht and Schrater 2007).

The degree to which these volitional-movement findings apply to balance-recovery reactions is unclear. The consequences of reduced accuracy are inherently more severe during balance recovery, as the failure to grasp a support securely could lead to a fall. There may be some leeway when targets are relatively large or when contact-related somatosensory feedback can be used to guide corrective adjustments during ‘target acquisition’ (Salimi et al. 1999; Debowy et al. 2001; Gardner et al. 2007); however, it is still necessary to achieve a minimum accuracy level (i.e. contact with the handhold) in order to achieve a functional grip that can contribute to stabilizing the body. While it is clearly possible to trade reduced speed for increased accuracy in voluntary peripheral-vision-guided reaching (Binsted and Heath 2005), perturbation-evoked arm reactions must be initiated and executed very rapidly to avert a fall, and it appears that even delays as small as 50 ms in achieving handhold contact can significantly increase risk of falling in older adults (Maki et al. 2001).

The objective of this study was to determine how the CNS resolves these speed-accuracy trade-offs when forced to rely on peripheral vision to guide a reach-to-grasp reaction evoked by an unpredictable balance perturbation. A task condition allowing full central vision of the handhold was used as a basis for comparison. Given the potential attentional demands associated with the visual processing of handhold location, we also included a task condition in which subjects performed a cognitive task that required them to maintain ‘straight-ahead’ central fixation of a computer screen. This task condition simulates the ‘real-life’ situation in which loss of balance occurs while engaged in an ongoing task that requires overt visual attention. To simulate the ‘real-life’ demands of monitoring ongoing changes in the locations of potential handholds, we used a new ‘moveable handhold’ protocol, in which the subject is stationary and the variation in the relative location of the handhold and body that normally occurs as a result of ambulation is instead introduced via movement of the handhold (Cheng et al. 2008). This approach allows precise control of visual inputs that would be very difficult to achieve using a gait-perturbation protocol. To maximize unpredictability, the handhold was controlled to move to, and stop at, several different ‘dwell’ positions (corresponding to pre-selected visual angles), prior to the delivery of the balance perturbation. To heighten accuracy demands, the size of the handhold was restricted to be only 25% larger than the width of the subject’s hand.

We hypothesized that a forced reliance on peripheral vision would lead to some reduction in the accuracy with which the handhold was grasped, in comparison with the central-vision condition, but would not significantly reduce the ability to achieve a successful functional grasp. Although we did not expect the changes in visual conditions to result in any changes in the timing of the response initiation or completion, we did hypothesize that performing the concurrent cognitive task would lead to a slowing of response initiation and completion, given that such dual-task interference effects have been observed to occur even in the absence of any visual-field restrictions (Quant et al. 2000).

Methods

Participants

Twelve young adults (6 men, 6 women; age 22–29 years; height 1.56–1.82 m; mass 43–90 kg) participated in this experiment. Subjects were all right-hand dominant, had a minimum corrected Snellen visual acuity of 20/40 and a minimum contrast sensitivity of 21 dB (as determined using the Melbourne Edge Test), and reported no sensory, neurological, or musculoskeletal problems. Subjects who required corrective lenses were permitted to wear them throughout the experiment. The institutional ethics review board approved this study, and each participant provided written informed consent.

Equipment

Reach-to-grasp reactions were evoked using a large (2 m × 2 m) computer-controlled platform that could translate suddenly in the horizontal plane to produce unpredictable balance perturbations (Fig. 1a). The subject stood in a comfortable, standardized stance position (McIlroy and Maki 1997) near the middle of the platform. Foam blocks surrounded the feet to deter subjects from stepping in response to the platform movement, thus reinforcing a reliance on compensatory grasping reactions (Fig. 1b). A safety harness was worn to prevent falls.

The target handhold was a cylindrical ‘handle’ (3.2 cm in diameter, 19 cm long) that was attached to a computer-controlled apparatus that generated horizontal linear motion of the handhold in the frontal plane, as shown in Fig. 1a, c (Cheng et al. 2008). The handhold and ‘handhold mover’ were positioned to the front and right of the subject and oriented such that the longitudinal handhold axis was horizontal and parallel to the frontal plane. The handhold position was adjusted for each participant so that the height of the handhold axis was 60% of body height and the anteroposterior distance between this axis and the back of the heels was 33% of body height. To provide moderate visual contrast, the handhold was covered with medium-gray grip tape, while the visual background (floor and wall) was black. The ambient room-illumination level was ~230 lux. A black foam-rubber collar was mounted at the lateral (right) end of the handhold and used to restrict the graspable length of the handhold to 125% of the subject’s hand width. Black tape was used to form a padded cover (8 mm wide, 43 mm in diameter) over the medial (left) end of the handhold, both for safety and to clearly delineate the edge of the target region for grasping (Fig. 1d).

A 15-inch computer monitor was mounted at the intersection of the floor and the front wall of the motion platform, 1.3 m in front of the subject (at 0° of visual angle) and tilted backward at an angle of 20° to vertical (Fig. 1a, d). This monitor was used to display either a static fixation point or the stimuli for the vigilance task, as detailed below. In both cases, the display stimulus was presented at 0° of visual angle with respect to the mid-point between the eyes (center of the screen) and the height of the display stimulus was adjusted such that the required downward gaze angle for central fixation of the stimulus approximated that of a point two steps ahead of the participant, a common gaze location during normal walking (Patla and Vickers 2003; Marigold et al. 2007).

Protocol

Three main task conditions were tested: (1) central vision (CV), (2) peripheral vision (PV), and (3) peripheral vision plus vigilance (PV + V). In the CV condition, subjects were simply asked to look directly at the handhold and to grasp it as quickly as possible when they felt the platform move. In the PV condition, a large (56 × 62 mm) black “X” was shown against a white background on the computer monitor mounted in front of the subject. Subjects were instructed to fixate on this “X” and to continue doing so until it disappeared (2.0 s after the onset of the platform perturbation). Compliance with this condition forced the subjects to rely on peripheral vision to monitor the handhold location. The PV + V trials similarly required subjects to rely on peripheral vision but included the additional demands of performing a concurrent cognitive task. A visuo-cognitive task was used in order to reinforce fixation of the target: in place of the “X” displayed on the monitor during PV trials, a randomly generated sequence of lower-case letters was displayed, one at a time, with the display changing every 250 ms. Subjects were asked to count the number of times they saw the letter “h”. This display continued for 2.0 s after the platform-perturbation onset. As in the PV condition, subjects were instructed to maintain fixation on the visual stimulus until the screen went blank at the end of the trial. Compliance with the instructions regarding eye movements was monitored using a lightweight, head mounted, binocular video-based (60 Hz) eye tracker (model 501, Applied Science Laboratories, Bedford, MA, USA). Subjects were informed that if they made saccades away from the fixation point during the PV or PV + V trials, their chances of winning a \$50 prize for fastest reaching performance (described in more detail below) would be reduced.

After completing four practice trials (to ensure that the subject understood the task conditions), each subject performed five blocks of trials. Each trial block comprised 18 perturbation trials (3 task conditions × 2 fall directions × 3 final handhold locations), plus one to three ‘catch’ trials in which the platform did not move. The order of trials within each block was randomized.

In each trial, the handhold started at a ‘home’ position to the right of the subject’s midline at a visual angle greater than 55°. Prior to the onset of each platform perturbation, the handhold was controlled to make one to four discrete movements, with each movement ending at one of the seven possible ‘dwell’ positions, where the handhold would pause for 0.5–3.0 s before moving to the next position. Each handhold movement took 0.4–1.3 s to complete, with the maximum handhold velocity limited to 0.48 m/s. Platform acceleration began between 1.0

and 3.0 s after the handhold reached its final position. Three final handhold locations were tested, corresponding to visual angles of 20°, 30°, and 40° (as measured to the medial end of the gray target region of the handhold, relative to the right eye Fig. 1c). The intermediate 'dwell' positions also included visual angles of 15°, 25°, 35°, and 45° to increase unpredictability. The three final positions were determined, using standard anthropometric data (Winter 1990; Tilley and Henry Dreyfuss Associates 2002), to correspond approximately to shoulder-handhold distances of 37, 38, and 42% of body height, respectively, when the subject is standing upright in the starting position.

Two perturbation directions were tested, involving (1) forward platform translation (acceleration amplitude 1.15 m/s²; maximum velocity 0.35 m/s; displacement 0.10 m) that induced backward falling motion and (2) backward translation (acceleration amplitude 1.75 m/s²; maximum velocity 0.53 m/s; displacement 0.16 m) that induced forward falling motion. In each case, the waveform comprised a 300 ms approximately-square acceleration pulse, followed immediately by an equal and opposite deceleration pulse. In 10% of trials, the platform did not move. These 'catch' trials were included to discourage anticipatory initiation of the arm movement and were delivered most frequently early in the test session to reinforce to the subject that the platform would not necessarily move in every trial.

Subjects were instructed to recover balance by grasping the gray region of the handhold as quickly as possible after the onset of the platform motion. They were also told not to move their feet. Additional motivation to produce rapid grasping responses was provided in the form of a \$50 prize, awarded to the subject who achieved the quickest average response time. Subjects were asked to start with arms relaxed by their sides and hands forming 'loose' fists (all digits relaxed, fingers flexed with the thumb 'on top') and were instructed not to move their arms or hands until they could feel the floor move. They were told that premature initiation of arm movements would result in a penalty that reduced their chances of winning the \$50 prize.

To prevent use of auditory cues to aid in detecting or tracking handhold motion, subjects wore headphones that played masking noise (recordings of sounds made by the handhold mover) throughout the duration of each trial. To simulate the directionality of the handhold-mover sounds, the masking noise was only played through the right headphone speaker. The volume was tuned through pilot testing to be approximately equivalent to the volume of sounds made by the handhold mover, as perceived while wearing the headphones.

Data collected

The arm reactions were recorded by four video cameras, three located overhead and one located to the far left of the subject and aligned approximately with the handhold axis. These recordings were used to classify reactions as to whether a 'successful' grasp of the handhold had been achieved and whether the end-point of the reach was accurate (on target). Example grasps are shown in Fig. 2. The final position of the hand was deemed to represent a 'successful grasp' if one or more digits were wrapped around the handhold. A response was considered 'on-target' if the final hand position placed the entire hand-width within the gray portion of the handhold, as per the subject instructions. 'Off-target' responses included (1) grasping the medial end of the handhold, with some portion of the hand extending beyond

the edge of the gray target area; (2) collision of the hand with the black foam barrier located at the lateral end of the handhold; or (3) collision of the back of the hand, thumb, or fingers with the handhold.

Electromyographic (EMG) recordings from the right medial-deltoid muscle were band-pass filtered (10–500 Hz) and sampled at 1,000 Hz. EMG-onset latency was determined by a computer algorithm (McIlroy and Maki 1993) and confirmed by visual inspection. Force-sensing resistors mounted on the front, back, and top surfaces of the handhold were sampled at 200 Hz and used to identify the time of handhold contact. These timing measures were both defined relative to onset of perturbation (platform acceleration $>0.1 \text{ m/s}^2$). Movement time was calculated as the time from deltoid onset to handhold contact.

Kinematic data for the right arm and hand, collected at 200 Hz using a three-dimensional optoelectronic (infrared) motion-analysis system (Motus 8, Vicon-Peak Performance, Oxford, UK), were used to characterize the reach trajectories in more detail. Reflective markers were placed on the right shoulder (acromion process), wrist (styloid process), and hand (distal end of the 3rd metacarpal). The recorded coordinates for these markers were low-pass filtered at a cut-off frequency of 6 Hz using a dual-pass fourth-order Butterworth filter (Gage et al. 2007). Data for the right wrist were used to determine maximum resultant velocity (relative to the right shoulder) and ‘time after peak velocity’ (i.e. the time interval between peak velocity and handhold contact), expressed in terms of both actual duration and a percentage of total movement time.

Data from the hand marker (relative to the platform frame of reference) were used to describe the trajectory of the reach in the horizontal plane. Trajectory data were used to determine (a) the angle of the reaching response at 10, 20, and 30% of the total distance to the handhold and (b) the deviation from a ‘direct path’ to the target region on the handle, using a method adapted from studies of volitional reaching and sweeping movements and described by Khan et al. (2006). The ‘direct path’ was defined as the straight-line path connecting the initial hand position (at movement initiation) to the target region of the handhold. The orthogonal deviation from this ‘direct path’ (in the horizontal plane) was calculated at increments of 10% of the total longitudinal distance. Note that while the ‘ideal’ (zero-deviation) location on the target region of the handhold was based on the average end-point of on-target grasps performed when the subject had central vision of the handhold, the width of the target region (125% of subject hand width) allowed for some variation in hand position (average allowable variation in hand position 21 mm; range 16–33 mm).

Statistical analysis

Repeated-measures analysis of variance (ANOVA) was performed to assess the main effect of task condition on each of the four primary variables used to characterize the speed-accuracy trade-offs: (1) frequency of successful grasping, (2) frequency of accurate reaching, (3) onset timing of the deltoid activation, and (4) handhold-contact time. Perturbation direction and handhold location were included as additional factors within the ANOVA. Significant two- or three-way interactions were interpreted by performing post hoc one-way analyses (repeated-measures ANOVA and Tukey multiple comparisons), so as to determine the effect of task condition within each of the six possible combinations of

perturbation direction and handhold location. Secondary kinematic measures were also analyzed using the same statistical model as the primary variables. All data were rank-transformed prior to analysis. This procedure avoids errors arising from potential violations of the assumptions underlying the ANOVA model and is equivalent to performing a non-parametric test (Conover and Iman 1981).

For the frequency variables, the proportion of trials in which the event was observed was calculated within each subject, for each of the 18 experimental conditions (3 task conditions $\times$ 2 fall directions $\times$ 3 handhold locations), and the ANOVA was performed on the rank-transformed proportions. For all of the other variables, rank-transformed data from individual trials were used. Trials in which subjects initiated the arm movement prematurely [EMG-onset latency <40 ms; (Maki et al. 1998)] and PV or PV + V trials in which the subject executed one or more saccades toward the handhold were excluded from the analysis. In addition, 101 trials were excluded from the primary analyses and 87 from the secondary analyses due to technical problems. Data from two subjects who relied primarily on an underhand grasp style were excluded from the trajectory analyses because the hand marker could not be tracked reliably in the later phases of the reach trajectory, and the remaining data were insufficient to perform reliable within-subject comparisons.

Results

Compliance with the task instructions was very high. For the task conditions that required subjects to use peripheral vision to monitor the changes in the location of the handhold, saccades away from the fixation point occurred in only 9% (34/360) of PV trials and 1% (4/360) of PV + V trials. The incidence of prematurely initiated arm movements (EMG latency <40 ms) was only 0.3% (3/1015 trials). Reaches toward the handhold occurred in over 99% (1007/1015) of trials, and subjects were able to achieve a functional grasp of the handhold in more than 90% of trials (mean within-subject 'functional-grasp' frequency $\pm$ SD: $93 \pm 18\%$). As hypothesized, the functional-grasp success rate was not affected by task condition ($F_{2, 22} = 1.72$; $P = 0.20$; Fig. 3a).

The frequency of accurate reaches, i.e. those which landed within the designated target area on the handhold, was $75 \pm 23\%$, somewhat lower than the functional-grasp success rate. In line with our hypotheses, the reach-accuracy success rate did show a main effect due to task condition ($F_{2, 22} = 4.62$; $P = 0.021$), although the interpretation of these data is complicated by a three-way interaction between task condition, fall direction, and final handhold location ($F_{4, 44} = 3.12$; $P = 0.025$). As illustrated in Fig. 3b, there was a trend for the reach-accuracy success rate to be lowest in PV + V trials, although this was largely limited to the most peripheral handhold location (40° visual angle). For this handhold location, the reach-accuracy success rate was only $56 \pm 26\%$ in PV + V trials, in comparison with rates of $69 \pm 28\%$ and $73 \pm 22\%$ in the PV and CV trials, respectively.

Analyses of the timing variables showed a minimal effect of task condition on the timing of deltoid-onset latency, but a far more pronounced effect on the time to handhold contact. Deltoid latency (Fig. 3c) did not exhibit any statistically significant main effects due to task condition ($F_{2, 22} = 1.41$; $P = 0.27$). In contrast, handhold-contact time showed a highly

significant main effect of task ($F_{2, 22} = 19.1$; $P < 0.0001$). Investigation of the causes of a significant three-way interaction (task X handhold location X fall direction; $F_{4, 44} = 6.26$; $P = 0.0004$) revealed that the most pronounced task effects occurred when the handhold was in the 40° position, as illustrated in Fig. 3d. Post hoc comparisons ($\alpha = 0.05$) showed that contact with the handhold in this location occurred significantly later (by ~ 90 ms, on average) in the PV + V trials than in the CV trials, regardless of fall direction. Although the timing differences were reduced at lower visual angles, this same pattern was evident for all handhold positions and both fall directions and statistically significant in two cases (30° /forward-fall, 20° /backward-fall trials). Mean handhold-contact times for responses executed in the PV condition tended to be intermediate to the CV and PV + V contact times and differed significantly ($\alpha = 0.05$) in three cases (PV > CV for 40° /backward-fall and 30° /forward-fall trials, PV < PV + V for 40° /forward-fall trials).

Secondary analyses were performed on selected kinematic measures, in an effort to gain further insight into task-related differences in the control of the reach-to-grasp reactions. Maximum wrist velocity was found to be similar for all task conditions (PV 2.69 ± 0.61 m/s, PV + V 2.62 ± 0.59 m/s, CV 2.74 ± 0.64 m/s; $F_{2, 22} = 2.29$; $P = 0.13$), across all handhold positions and both perturbation directions (no significant interactions, P 's > 0.23). However, task condition did have a main effect on movement time, with faster movements occurring in the CV trials than in either of the peripheral-vision conditions (PV 331 ± 142 ms, PV + V 348 ± 120 ms, CV 297 ± 87 ms; $F_{2, 22} = 21.2$; $P < 0.0001$). A significant three-way interaction ($F_{4, 44} = 4.49$; $P = 0.004$) and post hoc comparison of means ($\alpha = 0.05$) showed that this effect was largely limited to final handhold locations of 30° and 40° (for the 20° location, the only significant difference was a slower movement time in PV + V versus CV trials, during backward 'falls').

When the final handhold position was further in the visual periphery, the time after peak velocity was greater in both of the PV conditions than in the CV condition. The proportion of the movement time that came after peak velocity showed a significant main effect of task ($F_{2, 22} = 8.82$; $P = 0.0015$), unaffected by any interactions (P 's > 0.11). Post hoc comparisons of means ($\alpha = 0.05$) indicated that a greater proportion of movement time occurred after peak velocity in both peripheral-vision task conditions (PV and PV + V) than in CV (PV $30 \pm 23\%$, PV + V $28 \pm 23\%$, CV $24 \pm 20\%$). This difference, viewed in terms of absolute time after peak velocity, also showed a highly significant main effect of task ($F_{2, 22} = 23.25$, $P < 0.0001$), with CV values consistently lower than those in either peripheral-vision condition (PV 138 ± 131 ms, PV + V 140 ± 103 ms, CV 106 ± 68 ms). Post hoc analysis of a significant two-way interaction (task X handhold location; $F_{4, 44} = 3.20$; $P = 0.022$) showed a trend for these differences to increase as the handhold was viewed at higher visual angles.

Further analysis of the hand trajectories was performed to seek evidence of differences in control strategies between task conditions. Deviation from a 'direct path' between the starting hand position and target location on the handhold was compared across task conditions at increments of 10% of the total distance to be travelled. Significant main effects of task were found at all stages between 10 and 90% of the total movement distance ($F_{2, 18} > 4.44$, p 's < 0.03). Post hoc comparisons of means ($\alpha = 0.05$) uniformly showed deviations to be lower for CV than for PV and PV + V. A significant interaction (task X handhold-

location; $F_{2, 18} > 4.44$, p 's < 0.03) was found from 30 through 90% of the total movement distance. Inspection of mean trajectory deviations, shown in Fig. 4, clearly shows that the task-related difference in deviations become more pronounced as the handhold is viewed at greater visual eccentricities, especially in the early phases of the trajectory. Generally, deviations for the CV condition were lower than those for the PV and PV + V conditions, and these differences were significant through a greater proportion of the trajectory as the visual angle increased. Analysis of the initial trajectory angles (relative to 'straight ahead') also shows significant effects of task for the first 10% ($F_{2, 18} = 18.93$, $P < 0.0001$) and 20% ($F_{2, 18} = 7.54$; $P = 0.004$) of the movement distance, uncomplicated by any interactions ($F_{2, 18} = 1.23$, P 's > 0.32). Post hoc comparisons of means ($\alpha = 0.05$) show that the trajectory angles for PV and PV + V trials are significantly lower than for the CV trials (at 10%: PV $-1.4^\circ \pm 20.2^\circ$, PV + V $-0.4^\circ \pm 17.3^\circ$, CV $6.5^\circ \pm 20.5^\circ$; at 20%: PV $3.9^\circ \pm 17.9^\circ$, PV + V $4.8^\circ \pm 15.7^\circ$, CV $10.7^\circ \pm 18.1^\circ$). However, there is still a strong main effect of final handhold location (p 's < 0.0001), with significant differentiation between the trajectory angles for all three handhold locations.

To examine whether there was any evidence of learning or adaptation over the course of the experiment, we tabulated the mean values for the first trial block and the final (fifth) trial block, for some of the key response measures (Table 1). The experiment was not designed to permit statistical analysis of these data; however, inspection of the tabulated data does suggest some possible trends. The changes appeared to be most pronounced in the PV + V trials, with earlier rail contact and more direct trajectories appearing in the later trials. Most of the measures changed relatively little in the CV and PV tasks, with one exception: at the 40° handhold position, there was an apparent tendency (in all three task conditions) to reduce the amplitude and velocity of movement required by grasping the near-end of the handhold. This led to a reduction in frequency of 'on-target' grasps in the later trials, but the responses were still functionally adequate, as evidenced by a continued high frequency of successful grasps.

Discussion

As hypothesized, the frequency of successful grasping reactions was very high ($>90\%$) and was unaffected by whether central or peripheral vision was used to locate the handhold or by the attentional demands of engaging in a concurrent visuo-cognitive task. This finding is consistent with our expectation that the CNS would prioritize achieving successful functional contact with the handhold, regardless of task condition, in order to safeguard postural stability. However, we also expected that the reduction in spatial acuity in peripheral-vision trials would force the CNS to sacrifice reach accuracy to some extent in order to preserve a rapid speed of response. This hypothesis was not well supported by the findings, as the frequency of accurate reaches was comparable in all task conditions. Although, in general, it was possible to use peripheral vision to achieve a functionally useful degree of reach accuracy (sufficient for handhold contact) without sacrificing speed in initiating or completing the reach, evidence of a substantial decrement in speed (~ 75 ms delay in handhold-contact time) when reliant on peripheral vision did emerge in the most challenging condition, i.e. when the handhold was located in the extreme periphery and the subject was falling backward (away from the handhold). Consistent with our final

hypothesis, the concurrent task did appear to exacerbate the delay in contacting the handhold, but there was no support for our expectation that the response initiation would also be slowed under this task condition.

Given the absence of any task effects on response initiation (deltoid latency), it follows that the aforementioned delays in handhold-contact time must be due to an increase in movement time. Explicit analysis of the movement time data confirmed that reaches guided by peripheral vision to handhold locations of 30° and 40° took significantly longer than the equivalent reaches guided by central vision, and an analysis of the wrist trajectories indicated that less direct paths were used for reaches guided by peripheral vision than for those guided by central vision. These trajectories appear to have been less direct primarily because of a tendency for a lateral undershoot early in the movement (first 20%), as reflected in the initial trajectory angle data. While the differences in initial trajectory did not lead to any significant declines in the accuracy of the final grasp, the increased time-after-peak-velocity may have been related to a need to compensate for a less accurately aimed reach by allowing for the use of online corrections (Chua and Elliott 1993; Elliott et al. 2001; Khan et al. 2006).

An increased time to contact the grasp target when dependent on peripheral vision has also been reported in a study of volitional reach-to-grasp (Sivak and MacKenzie 1990), and it has been proposed in numerous studies of volitional reaching and pointing movements that a prolongation of the time after peak velocity serves to 'buy' the additional time needed for online corrections to the arm trajectory (for a review, see: Khan et al. 2006). In Sivak and Mackenzie's study, as in ours, the majority of the additional time taken to grasp the target when dependent on peripheral vision occurred after the peak wrist velocity. When expressed as a proportion of movement time, the mean difference (PV minus CV) was three times larger in our study than in theirs (8% vs. 2.4%); but in absolute terms, our effect size is much smaller because our perturbation-evoked reactions were much more rapid. In our study, the mean time after peak velocity was 105 ms in central-vision trials and 139 ms in peripheral-vision trials, whereas the corresponding values in the study by Sivak and Mackenzie were 712 and 1,069 ms. Nonetheless, studies of volitional reaction-time pointing and reaching movements suggest that even the relatively small mean increase in time after peak velocity observed in our PV trials (34 ms) may be sufficient to facilitate the execution of online trajectory corrections (Paillard 1996).

The delays in handhold-contact time associated with the dependence on peripheral vision tended to be exacerbated when subjects performed the concurrent visuo-cognitive task. Although the difference between the PV and PV + V tasks was statistically significant in only two experimental conditions (forward falling motion, 40° handhold location; backward falling motion, 20° handhold location), the addition of the cognitive task increased (from two to four) the number of conditions in which the peripheral- and central-vision handhold-contact times differed significantly. In terms of effects on the accuracy of the response, a functional level of grasp accuracy was almost always achieved. The success rate with which the hand was placed within the specified target region of the handhold appeared to drop by a modest amount (mean ~15%) in the PV + V trials, when the handhold was at the 40° location, although this was not statistically significant. Overall, these results suggest that the

concurrent cognitive task had a modest effect, at most, on the speed and accuracy of reaches guided using peripheral vision.

We had also expected the addition of the cognitive task to significantly delay reaction initiation, based on previous findings that a mental arithmetic task (counting backward by serial 7's) led to a 40-ms delay in deltoid latency during reach-to-grasp reactions evoked by chair-tilt perturbations (Quant et al. 2000); however, we found no evidence to support such an effect. The discrepancy in findings could possibly be due to differences in the nature of the cognitive task and/or method of perturbation. We are not aware of any other studies that have examined the effects of cognitive tasks on upper-limb balance reactions; however, there have been a substantial number of dual-task studies involving lower-limb balance reactions. Our results are consistent with these studies, which have generally found that competing attentional demands tend to affect later phases of the balance-recovery reactions, but not the initiation phase (e.g.: Brown et al. 1999; Rankin et al. 2000; Brauer et al. 2002; Redfern et al. 2002; Zettel et al. 2005; Maki and McIlroy 2007; Zettel et al. 2008).

The findings of the present study are likely dependent, at least to some extent, on the specific handhold dimensions and perturbation characteristics that were used. Clearly, larger perturbations would place greater demands on the speed of response, whereas a smaller handhold would increase demands on accuracy. Given that the handhold that we used is much smaller than the handrails and grab-bars that are typically found in 'real-life' environments, the capacity of our subjects to rely on peripheral vision to localize and grasp our relatively small target supports the idea that peripheral vision may play an important role in guiding functional reach-to-grasp balance-recovery reactions in 'real-life' environments. With regard to the perturbations, we elected to use relatively small perturbations in this initial study in order to prevent stepping reactions from being evoked. Presumably, larger perturbations will require larger stabilizing hand-handhold reaction forces to be generated and hence may require a stronger grip. Some of the 'partial' grips that were sufficient to stabilize the body in the present study may prove to be inadequate in responding to larger perturbations; hence, grasp-accuracy demands may increase. In addition, larger perturbations will demand more rapid responses. Further work is needed to determine whether the increased accuracy and speed-of-response demands imposed by larger perturbations will affect the extent to which peripheral vision can be used to guide functionally effective reach-to-grasp reactions.

In the present study, we elected to standardize the handhold dimensions relative to the subject's hand width in order to maintain consistent mechanical demands for endpoint accuracy control. However, a consequence of this was that the visual size of the target varied depending on target angle. For 11 of the 12 subjects, the handhold width ranged between 8 and 10 cm, resulting in minimal variation in the angles subtended by the handhold: 6.3°–7.8° at the nearest (20°) position and 4.1°–5.1° when the handhold was at the furthest (40°) position. The target size for the remaining subject was 16 cm, which subtended angles ranging from 6.0° to 10.8°, depending on handhold position. Despite this difference, this subject's average outcomes for all measures were similar to the other subjects and never represented the most extreme values. Thus, while our method of standardizing handhold

length may have introduced some variation in the visual difficulty of the task, there was evidently no substantial impact on the results of the experiment.

The ‘moveable handhold’ paradigm was used in this study in order to avoid a number of methodological problems associated with more ‘ecologically valid’ approaches to studying the visual control of balance-recovery reactions. Such approaches would involve applying a balance perturbation as the subject moves within the environment, and recording the gaze behavior that occurs. While we used this approach in previous and ongoing studies (Scovil et al. 2007; King et al. 2009; King et al. in press), there are a number of practical limitations: (1) gait variation precludes precise control over the motion and position of the body, relative to the handhold, at perturbation onset; (2) this variation precludes precise control of central and peripheral visual inputs; and (3) subjects are likely to learn proactive, adaptive strategies after the first trial. The ‘moveable handhold’ approach avoids these problems by having the subject remain stationary and moving the handhold to introduce the relative motion that would normally occur as a result of ambulation (Cheng et al. 2008).

However, this ‘moveable handhold’ approach has its own limitations that may potentially limit the generalizability of the findings to ‘real-life’ loss-of-balance situations. For example, the perturbations, while unpredictable in timing and direction, were nonetheless fully expected by the subjects, whereas the ‘real-life’ perturbations that precipitate falls are likely to involve unexpected events. Furthermore, the administration of multiple trials provided opportunities for learning and adaptation (e.g., Nashner 1976; Horak and Nashner 1986; Keshner et al. 1987; McIlroy and Maki 1995a; Marigold and Patla 2002; Pavol et al. 2004) that would not be available in typical ‘real-life’ loss-of-balance situations. As highlighted by the data in Table 1, the repetition of the trial blocks did, in fact, appear to allow improvement in performance of the most demanding task condition (i.e. improved speed, accuracy, and trajectory path in PV + V trials) and changes in strategy for the most demanding handhold position (grasping the end of the handhold when it was at 40°), although the changes were generally quite small in magnitude.

Another limitation pertains to the intermittent nature of the handhold motion and the predictability of certain features of the handhold location (e.g. height and frontal distance, maximum extent of handhold motion), whereas the relative motion between subject and handhold that occurs as a result of ambulation in daily life leads to continuous, and much greater, variation in relative handhold location. Ambulation also introduces ongoing lower-limb motor activity that was not present in this experiment, and which has been shown to delay the onset of compensatory arm motion, possibly due to difficulty in detecting onset of instability amidst the sensory discharge associated with the ongoing limb motion (Quant et al. 2001). Ongoing arm swing may also influence the speed of response, although, to our knowledge, the effects of this have not yet been reported. Although we did simulate the effect of the competing attentional demands that would be likely to occur in daily life, the vigilance task that we used required a fairly low cognitive load (Berardi et al. 2001). Visuospatial tasks would be more likely to affect the reactions, due to the potential competition for the cognitive resources involved in spatial processing (Maylor and Wing 1996; VanderVelde et al. 2005), and cognitive tasks that include a motor component, such as verbal articulation, would also be expected to increase ‘dual-task interference’ effects

(Yardley et al. 1999). In addition, the simplicity of the test environment minimized the attentional demands of the ‘visual search’ that would normally need to be carried out to locate a handhold in the periphery, and the static nature of the task removed any attentional or visual demands that may be associated with normal tracking of the environment during locomotion, such as processing and interpreting optic flow.

Nonetheless, despite these limitations, the findings of this study contribute to increasing our understanding of the CNS control of rapid reach-to-grasp balance-recovery reactions and provide a baseline for ongoing and future studies to address the effects of factors such as aging, sensorimotor disorders, neurological disease, and medication use. Studies focusing on older adults are expected to be particularly important in relation to the problem of falling, because it is known that while older adults are even more likely than young adults to grasp handrails for support (McIlroy and Maki 1996; Maki et al. 2000; King et al. 2009), the capacity of many older adults to use peripheral vision is limited by either sensory (e.g. glaucoma, retinis pigmentosa) or attentional (e.g. reduction in ‘useful field of view’) impairments (Owsley et al. 1995; Geruschat et al. 1998; Sekuler et al. 2000; West et al. 2002; Turano et al. 2004; Cedrone et al. 2008). Conversely, reliance on peripheral vision may be the only option for people with macular degeneration. The paradigm used in this experiment can also be used to investigate the efficacy of clinical interventions, such as the “visual-training” programs we are currently studying (McKay et al. 2008) or the effects of wearing contact lenses, bifocals, or other types of visual aids. Given the evidence suggesting that use of peripheral vision to guide compensatory reach-to-grasp balance-recovery reactions may be a common strategy naturally adopted by both young and older adults (King et al. 2009; King et al. in press), the capacity to better understand, and counter, the impaired ability to use this strategy may ultimately help to reduce the risk of falls for older adults.

Conclusion

The results of this study indicate that peripheral vision can be used to guide rapid perturbation-evoked reach-to-grasp reactions with a level of accuracy that is sufficient to achieve a functional grasp, even when the handhold is small and the location of the handhold is varied in an unpredictable manner prior to perturbation onset. These peripherally guided reactions were executed as rapidly as responses that were guided by continuously available central vision of the handhold, provided that the handhold eccentricity was low (20°); however, as eccentricity increased, movement paths became less direct and movement times increased, leading to a substantial delay (~75 ms, on average) in contacting the handhold at the highest visual angle (40°). Performance of an ongoing cognitive task had relatively little impact on the ability of the CNS to react quickly and accurately to grasp the handhold under the guidance of peripheral vision. Overall, our findings suggest that peripheral vision can be an adequate source of information for guiding functionally effective reach-to-grasp balance reactions, despite the increases in movement time that were observed. Further work is needed to establish whether this remains the case when responding to larger perturbations, and to determine the effects of age-related impairments in the capacity to process peripheral visual information.

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Fig. 1.

Methodological details. Panel **a** gives an overview of the experimental environment and shows how the 'handhold mover' was affixed to the moving platform, and how the handhold position was adjusted relative to each subject's height (H). Panel **b** shows a subject standing in this environment, grasping the handhold. Foam blocks placed around the feet restrict stepping, reinforcing reliance on reach-to-grasp reactions. Panel **c** shows the three final handhold locations that were used, as calculated relative to the position of the right eye. Panel **d** shows the target region of the handhold, with black tape delineating the medial end of the target region and a black foam barrier forming the lateral boundary of the target. The location of the foam barrier was adjusted for each subject such that the target region was 125% of the subject's hand width

Fig. 2.

Grasp coding examples. Example grasps taken from the subject data are shown to clarify what is meant by ‘successful’ or ‘functional’ grasp and by an ‘accurate’ or ‘on-target’ grasp. Panel **a** shows a grasp that is both successful and accurate—the fingers wrap around the handle and the hand is entirely within the gray target region of the handhold. Panel **b** is a reference image of the handhold, aligned with panels **a** and **c**, to assist in visualizing the location of the target region of the handhold. In panel **c**, the grasp is functional but inaccurate (undershoots the target). The fingers are wrapped around the handhold to provide secure support, but the hand is covering the taped border that delineates the medial end of the target region. The grasp in panel **d** is also functional but inaccurate (overshoots the target). The hand does grasp the handle but has collided with the black foam-rubber barrier that forms the lateral border of the target region. Panel **e** shows an unsuccessful attempt to grasp the handhold. Contact is only made with the backs of the fingers, which do not wrap around the handle in any way

Fig. 3.

Effect of task condition on the primary variables. These graphs show mean values for each of the primary variables per the one-way post hoc ANOVAs and multiple comparisons ($\alpha = 0.05$). Mean effects of task condition are shown for each fall-direction X handhold-location combination. *Error bars* indicate the standard deviation. Panels **a** and **c** show the consistency of functional grasp frequency and deltoid-onset timings. Note that in **b**, while none of the comparisons is significant, there is a trend to decreased accuracy in the PV + V condition when the handhold is located at the highest visual angle. In **d**, differences in handhold-contact times are shown. Note the trend for increased times to handrail contact in the PV + V condition (and to a lesser extent for the PV condition), when compared to CV. As shown, this trend was most pronounced at the highest visual angle

Fig. 4.

Trajectory deviations by handhold location and task condition. These plots show the mean deviations from a 'direct path' trajectory to the handhold for each task condition at each final handhold location, clarifying the meaning of significant two-way interactions between these factors found from 30 to 90% of the longitudinal distance. *Horizontal lines* for each plot indicate the 'zero deviation' direct path to the handhold. Values below this *line* indicate an undershoot (to the medial/left side) of the 'direct path'; values above the *line* are 'overshooting' to the lateral/right side of the 'direct path'. Indicators of significance for between-task comparisons of means ($\alpha = 0.05$) within each handhold location and distance point are indicated as follows: * CV is significantly different from PV and PV + V, † CV is significantly different from PV, § CV is significantly different from PV + V, and 'ns' where none of the means differ significantly from each other.

Mean values of key response measures in the first and final blocks

	CV		PV		PV + V	
	1st block	5th block	1st block	5th block	1st block	5th block
% successful grasps	100	100	100	100	97	100
% on-target grasps	80	84	72	71	67	69
Deltoid onset (ms)	160	163	147	159	164	168
Contact time (ms)	430	463	454	484	530	502
Movement time (ms)	220	235	251	261	310	272
Maximum wrist velocity (m/s)	2.97	2.65	2.93	2.64	2.67	2.62
Deviation from direct path (mm), averaged over the full trajectory	3.4	2.7	-8.8	-8.0	-25.9	-7.7
	20°		30°		40°	
	1st block	5th block	1st block	5th block	1st block	5th block
% successful grasps	99	100	99	100	100	100
% on-target grasps	80	85	68	79	73	57
Deltoid onset (ms)	155	160	162	162	155	168
Contact time (ms)	441	443	444	453	545	550
Movement time (ms)	226	216	223	230	303	301
Maximum wrist velocity (m/s)	2.85	2.68	3.00	2.63	2.73	2.59
Deviation from direct path (mm), averaged over the full trajectory	4.0	6.1	-9.8	-4.0	-25.3	-15.4