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ERRATUM

Erratum to: Eye–hand coordination in a sequential target contact task

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In the original publication of this article, Professor Johansson's name was wrongly spelled as 'Johannson'. It is now corrected here.

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RESEARCH ARTICLE

Eye–hand coordination in a sequential target contact task

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Abstract Most object manipulation tasks involve a series of actions demarcated by mechanical contact events, and gaze is typically directed to the locations of these events as the task unfolds. Here, we examined the timing of gaze shifts relative to hand movements in a task in which participants used a handle to contact sequentially five virtual objects located in a horizontal plane. This task was performed both with and without visual feedback of the handle position. We were primarily interested in whether gaze shifts, which in our task shifted from a given object to the next about 100 ms after contact, were predictive or triggered by tactile feedback related to contact. To examine this issue, we included occasional catch contacts where forces simulating contact between the handle and object were removed. In most cases, removing force did not alter the timing of gaze shifts irrespective of whether or not vision of handle position was present. However, in about 30% of the catch contacts, gaze shifts were delayed. This percentage corresponded to the fraction of contacts with force feedback in which gaze shifted more than 130 ms after contact. We conclude that gaze shifts are predictively controlled but timed so that the hand actions around the time of contact are captured in central vision. Furthermore, a mismatch between the expected and actual tactile information related to the contact can lead to a reorganization of gaze behavior for gaze shifts executed greater than 130 ms after a contact event.

Keywords Eye–hand coordination · Object manipulation · Visually guided · Reaching · Sensorimotor control

Introduction

When pointing or reaching to a single target, people usually direct their gaze to the target as they initiate their hand movement and maintain gaze on target until around the time that the hand arrives (Crawford et al. 2004; Desmurget et al. 1998; Gribble et al. 2002; Neggers and Bekkering 2000, 2001). This gaze behavior can improve reach accuracy in at least two ways. Looking at the target allows effective use of visual feedback of hand position to guide the hand to the target (Paillard 1996; Land et al. 1999; Carlton 1981; Berkinblit et al. 1995; Saunders and Knill 2004; Sarlegna et al. 2004). In addition, efferent and/or afferent signals related to gaze position can be used to guide the hand even when the hand is not visible (Prablanc et al. 1979, 1986, 2003; Prablanc and Martin 1992).

Many manual tasks involve a series of actions directed toward different target objects (Johansson et al. 2001; Land et al. 1999). These phases are often bounded by mechanical contact events that represent sub-goals of the task. For example, when picking up a hammer to strike a nail, contact between the digits and handle marks the end of the reach phase, the breaking of contact between the hammer and support surface marks the end of the load phase (during which vertical lift forces are applied to overcome the weight of the object), and contact between the hammer

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head and nail marks the end of the movement phase. In such tasks, gaze is typically directed to successive contact locations as the action unfolds, arriving before the hand (or object in hand) and departing around the time the sub-goal is completed (Ballard et al. 1992; Epelboim et al. 1995; Hayhoe and Ballard 2005; Johansson et al. 2001; Land et al. 1999; Flanagan and Johansson 2003).

In addition to improving manual accuracy through visual feedback and the use of gaze-related signals to guide the hand (or object in hand), directing gaze to contact locations may serve two further functions (Johansson et al. 2001; Flanagan et al. 2006). First, foveating a contact location at the time of contact may facilitate the comparison of predicted and actual visual consequences of action. By comparing predicted and actual sensory events related to contact (including visual, tactile and auditory events), the motor system can monitor task progression and adjust subsequent motor commands if errors are detected. Second, by aligning gaze with contact events, the sensorimotor system may be able to establish and maintain correlations between retinal and extraretinal signals and other sensory signals, including those from tactile receptors that arise from contact.

In manipulation tasks, a key question relates to how successive action phases are linked together. Specifically, is the execution of the next phase triggered by sensory information confirming that the goal of the current phase has been achieved, or is the next phase launched predictively, in advance of sensory goal confirmation? The answer to this question presumably depends on the particular task being performed, the behavioral context, and the certainty with which sensory outcomes can be accurately predicted. If the outcome of the current action phase can be predicted with confidence, then the next phase can be launched based on the predicted, as opposed to the sensed, goal completion. This strategy would allow for smoother and quicker phase transitions and thus more dexterous actions as compared to a strategy based on sensory verification of goal completion. Both predictive and reactive sequential phase control can be observed in object manipulation tasks. For example, in precision grip lifting, the transition between the load phase and the subsequent lift phase demarcated by the instance of object lift-off is usually predictive. That is, people normally scale the rate of change of force output to the predicted weight of the object such that load force drive at lift-off, which accelerates the object, results in a natural, smooth and critically damped lifting motion (Johansson and Westling 1988). However, when people are uncertain about object weight, they may employ a probing strategy whereby they keep increasing the vertical force intermittently, until lift-off occurs and only then terminate the load phase reactively (Gordon et al. 1991; Johansson and Westling 1988).

Because gaze is directed to successive movement goals in visually guided manipulation tasks, the degree to which action phases are linked reactively versus predictively can be posed at the level of gaze control. Given that eye movements are rapid, it is conceivable that gaze shifts from the current goal to the next could, in many situations, be delayed until sensory confirmation of goal completion is obtained. On the other hand, predictively shifting gaze to the next target, before completion of the current goal has been confirmed, may facilitate performance by allowing earlier use of visual and gaze-related signals linked to the next goal. Neggers and Bekkering (2000) examined the coupling between gaze and hand movement in a target-pointing task in which a second "gaze" target could appear during the pointing movement. Although participants were instructed to look at the gaze target as quickly as possible, while continuing to point to the hand target, they were unable to do so until about 50 ms (on average) after the fingertip contacted the target. This gaze anchoring, also seen when the hand was not visible (Neggers and Bekkering 2001), confirms the important role played by gaze position signals in guiding the hand toward the target. However, the fact that the gaze shifted so soon after contact suggests that commands specifying these shifts were initiated prior to sensory confirmation of the movement goal.

In the current study, we investigated the timing of gaze shifts in a task in which participants moved a handle, in a horizontal plane, to tap sequentially five virtual target objects. Simulated contact forces were applied to the handle and the targets were always visible. In different conditions, the position of the handle, during the movement, was either visible or invisible. Based on previous findings (Epelboim et al. 1995; Johansson et al. 2001), we predicted that, in the handle-visible condition, participants would typically shift their gaze proactively to the next target around the time of contact. In the handle-invisible condition, prediction of contact times in the visual modality may be less accurate and this could lead to more reactive gaze behavior, with gaze shifts occurring well after contact. To determine whether tactile feedback related to contact might trigger or facilitate gaze shifts to the next target, in both conditions we occasionally removed the force that simulated contact between the handle and a target object. If triggered by tactile feedback, gaze shifts would be delayed in these catch contacts.

Methods

Participants

Eight participants (18–24 years old) with normal or corrected to normal vision performed the task with their dominant right hand. The experimental protocol was conducted in accordance with local ethics procedures and took approximately 1 h to complete. Prior to testing, participants provided written informed consent and were later compensated for their time.

Apparatus

While seated, participants moved the handle of a lightweight force-reflecting robotic device (Phantom Haptic Interface 3.0L, Sensable Technologies, Woburn, MA, USA) to contact a series of five visible virtual target objects located in a horizontal plane placed approximately 40 cm below the eyes (Fig. 1a, b). The handle was a vertically oriented cylinder (2 cm in diameter and 10 cm in height) mounted on an air sled that slid across a horizontal glass surface. The position of the handle was recorded at 1,000 Hz with a spatial resolution of 0.1 mm. A projection system was used to visually display, in the same horizontal plane, the target objects (2 × 2 cm squares), a circle (2 cm-diameter) representing the position of the handle, and a start position (2 cm-diameter circle) for the handle. The start position was located 15 cm in front of the eyes in the midsagittal plane. The light gray boxes (4 × 2 4 cm) shown in Fig. 1b indicate the areas in which the centers of the five targets could be located on a given trial. The target locations were randomly selected from these areas, subject to the constraint that the distance between any two targets in the *x* direction was no less than 1 cm. The horizontal plane in which the targets and the handle and start positions were represented was aligned with the top of the handle and hence the location at which forces were imparted to the handle.

The robotic device provided force feedback to the hand by simulating contacts between the handle (i.e., the circle representing the handle) and the target objects. The handle was defined as being in contact with a target whenever the perimeter of the circular handle overlapped with the perimeter of the square target. The target objects were modeled with slightly compliant sides linked to the center of the object via a damped spring with stiffness and viscosity of 1,000 N/m and 0.00009 Ns/m, respectively. Because of the high stiffness of the target objects, the sides did not move appreciably during contact and we did not render target deformation visually. Images were displayed using an LCD projector (LC-XNB3S, Eiki Canada, Midland, ON) with a refresh rate of 60 Hz and a fixed (minimum) delay of 13 ms. Thus, in the handle-visible condition, there was an average delay of ~21 ms between the time the handle contacted an object (and contact forces were initiated) and the time the handle visually contacted the object.

An infrared video-based eye-tracking system (ETL 500 pupil/corneal tracking system, ISCAN Inc. Burlington, MA, USA), mounted below a headband, recorded the gaze position of the left eye at 240 Hz. A bite-bar was used to help stabilize the head. Gaze was calibrated using a two-step procedure: an initial 5-point calibration using ISCAN's Line-of-Sight Plane Intersection Software followed by a 25-point calibration routine. Calibration points (4 mm-diameter circles) were projected onto the horizontal plane where the targets were projected and distributed over a region that incorporated the hand start location and all possible target locations. The ISCAN calibration converted raw gaze signals into pixels from the line-of-sight camera and the 25-point calibration converted pixels (i.e., the

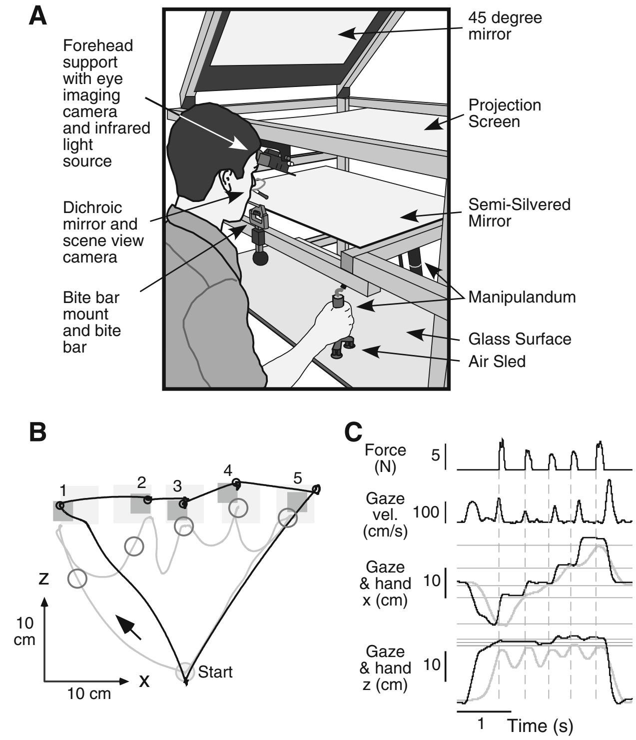

Fig. 1 Apparatus and task. **a** While seated, participants held a handle attached to a lightweight manipulandum. The handle was mounted on air sleds and could be easily moved over a horizontal glass surface. An image was projected onto a screen via a 45° mirror and viewed by the participant in a mirror. This image appeared at the level of the top of the handle. The image contained the targets, the start position for the handle and gaze and, in some conditions, a circle representing the position of the handle. A video-based eye tracker was used to record the position of the left eye and a forehead strap and small bite-bar were used to stabilize the head. **b** Top view of the five targets (*dark gray squares*) from a single trial in which visual feedback of hand position was provided. The *large light gray squares* represent the possible center locations of the five targets. The *gray and black traces* show the paths of the hand and gaze, respectively. The *small open black circles* represent gaze positions at the start of successive saccades between targets, and the *large circles* on the hand path represent the corresponding positions of the handle. The *arrow* indicates the initial direction of the hand at the start of the trial. In this trial, gaze shifted away from targets 1 and 2 before the target was contacted, and shifted away from targets 3–5 after contact. **c** Contact force, gaze velocity and gaze and hand positions in *x* and *z* as a function of time. The *horizontal lines* in the *lower two panels* show the *x* and *z* positions of the five targets. Note that two saccades were used to bring gaze to the first target and single saccades were observed between targets

output of the ISCAN calibration) into the coordinates of the Phantom in the horizontal plane. Gaze was calibrated at the start of the experiment and was checked following each block of trials (see below) so that, if necessary, gaze could be re-calibrated before starting a new test block. The spatial resolution of gaze in the horizontal plane of the hand, defined as the average standard deviation of all calibration fixations, was 0.36° visual angle. This corresponded to ~3 mm when gaze was directed to the center of the target zone for the middle (i.e., third) target.

Procedure

To initiate a trial, participants were required to maintain the handle and their gaze within 5 and 60 mm, respectively, of the center of the start position for 200 ms. A larger area was used for gaze because of the larger variability of the recorded gaze position. Vision of the handle position was provided during this initial phase of the trial. Five targets (dark gray boxes in Fig. 1b) then appeared and participants were asked to reach out and lightly contact, on the near surfaces, the targets from left to right before returning to the start positions. In the handle-invisible condition, vision of the handle was removed at the same time that the targets were displayed. At the end of each trial, text was displayed (30 cm distal to the start position in the horizontal plane) for 1 s providing feedback on movement speed and whether the targets had been contacted in the correct order. "Too Fast" or "Too Slow" were displayed if the average time interval between successive target contacts was less then 350 ms or greater than 750 ms, respectively, and "Wrong Order" was displayed if the targets were not contacted in the correct order. Otherwise, "Good" was displayed. Participants were not instructed where to look during the task.

All participants performed 60 training trials followed by two test blocks of 70 trials each. Visual feedback of the handle was provided in one test block (handle-visible condition) and removed in the other test block (handle-invisible condition). The order of these two blocks was counterbalanced across participants. Each test block of 70 trials contained 9 randomly selected catch trials in which force feedback related to contact was removed for one of the middle three targets in the sequence (i.e., the second, third or fourth target) with each of these targets used three times. Thus, out of the 350 contacts in a test block (70 trials × 5 targets), 9 (<3%) were catches. We kept the catch rate low to guard against the possibility that catches would alter behavior in the non-catch trials. When force feedback was removed, the handle could move through the target. Thus, in the hand-visible condition, participants received both visual and tactile feedback about contact in standard trials and only visual feedback during catch trials. In the hand-invisible condition, participants received tactile feedback related to contact in standard trials and no feedback during catch trials.

Analysis

Hand and gaze position in the horizontal plane where the targets were located and forces in the horizontal plane of hand movement were sampled at 1,000 Hz. This involved over-sampling the gaze data provided, at 240 Hz, by the ISCAN system. The ISCAN software applied a 10-point moving average to the gaze data (sampled at 240 Hz) resulting in an average delay of 20 ms. We therefore time advanced the gaze signal by 20 ms, so that the gaze data would be temporally aligned with the hand data. To detect saccades, we further smoothed the x and z gaze position signals (see coordinate system shown in Fig. 1b) using a fourth-order low pass Butterworth filter with a cut-off frequency of 6 Hz, double differentiated these signals to obtain x and y gaze accelerations, and computed the magnitude of the resultant gaze acceleration. When a saccade occurred, the resultant gaze acceleration featured two peaks and a saccade was deemed to occur if both peaks exceeded 5 m/s^2 and were less than 150 m apart. Once a saccade was identified, we used the gaze data provided by the ISCAN system to determine saccade start and end times. Saccade onset and offset times were defined as the times at which saccadic velocity first exceeded and dropped below 0.2 m/s, respectively. The x and z hand position signals were smoothed using a low pass fourth-order Butterworth filter with a cut-off frequency of 14 Hz.

We focused our analysis around contact attempts coded into three categories: correct hits, misses, and mishits. A correct hit occurred when a target was contacted in the proper order and any part of the handle contacted the near surface. Of the 5,145 contact attempts analyzed, 4,704 (91.4%) were correct hits. Misses, in which the handle failed to make contact with the target, occurred 169 times (3.3%), and mishits where the cursor contacted the left, right, or backside of the target occurred 272 times (5.3%). We excluded from analysis contact attempts that involved lost gaze signals, blinks and errors in contact order. We also excluded contact attempts immediately following misses, mishits or catch hits, because these events might influence behavior when contacting the subsequent target. Of the 6,161 total recorded contact attempts, a total of 1,016 (16.5%) were removed.

To characterize the timing of saccadic gaze shifts, we determined gaze arrival and exit times for each analyzed contact attempt. The gaze exit time was defined as the onset time of the saccade shifting gaze away from a target (to the next target) relative to the actual or estimated time at which the hand contacted the target (see below for details about estimated contact times in misses). The gaze arrival time was defined as the offset time of the saccade bringing gaze to a target relative to the actual or estimated time at which the hand contacted the target.

To assess hand behavior, we computed the hand path distance between successive target contacts as well as the hand movement duration between successive contacts. For each target, we also computed the hand approach angle and hand retraction angle based on the position of the hand at contact and the positions of the hand when entering and exiting a 3 cm perimeter around the hand contact position (see "Results"). Finally, we also determined the maximum contact force for each target contact. For all analyses, an alpha level of 0.05 was considered to be statistically significant.

Results

As illustrated in the single trial depicted in Fig. 1, participants performed the task by generating curved hand movements between the successive target objects (Fig. 1b). Participants almost always fixated each of the five targets well before the handle arrived and shifted gaze to the next target around the time the handle contacted the current target. In this particular trial, gaze shifted away from targets 1 and 2 before contact, but shifted away from targets 3–5 shortly after contact (Fig. 1b, c). Participants rarely directed their gaze to viewed position of the handle or any locations other than the target objects. Participants were quite accurate in shifting gaze to the targets, and gaze shifts between targets were generally achieved with a single saccade (Fig. 1c). As a consequence, corrective saccades bringing gaze on target were infrequent.

Hand and gaze accuracy

Figure 2a shows frequency distributions of the *x* position of the center of the handle at the time of target contact, or attempted contact, relative to the *x* position of the center of the target. For both the handle-visible and invisible conditions, separate distributions are shown for each participant. Each distribution includes all hits, mishits and misses. For mishits and misses, we took the *x* position of the center of the handle when the surface of the handle crossed the *z* position of the near surface of the target (i.e., where the handle would have contacted the target had the target been wider). For misses where the handle did not reach this *z* position, we took that *x* position of the center of the handle at the maximum *z* position of the handle (closest to the target along the *z* axis). When the center of the handle was within ±10 mm of the center of the target (gray region in Fig. 2a), a correct hit was registered provided the handle reached the target. When the center of the handle was outside ±20 mm of the center of the target (vertical dashed lines in Fig. 2a), a miss was registered. When the center of the handle was between 10 and 20 mm of the center of the

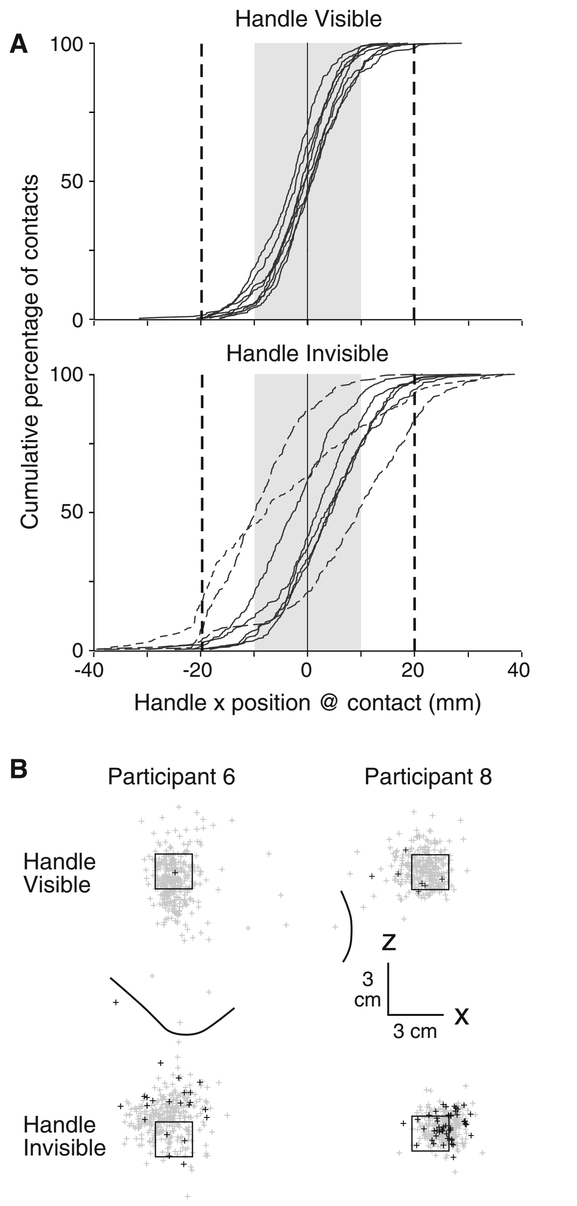

Fig. 2 Hand and gaze movement accuracy. **a** Cumulative distributions of hand *x* position at the time of contact, relative to the center of the target, when contacting targets with and without vision of the handle. Each *curve* represents the data from one of the eight participants. In each *panel*, the *filled gray bar* represents the width of the target. The *region* between the *dashed vertical lines* shows the range of handle positions that would enable a successful contact. The *dashed curves* in the *lower panel* show the three participants who most frequently missed or mishit targets when vision of the handle was not provided. **b** The *gray crosses* show the locations of fixations, relative to the target (*open black square*), associated with correct hits for two participants in the handle-visible and invisible conditions. The intermixed *black crosses* show fixations associated with misses and mishits

target and contact occurred, either a correct hit or a mishit could be registered depending on the angle of handle approach (see "Methods"). In the handle-visible condition, participants successfully contacted the near surface of the target in 98% of contact attempts. In the handle-invisible condition, correct hits were observed in 80% of all contact attempts. Mishits and misses were observed in 12 and 8% of attempts, respectively. Three participants accounted for most of these mishits and misses (see dashed curves in Fig. 2a) and the distributions for two of these participants appeared to be more variable.

To quantify the effect of vision of the handle on reach accuracy, for each participant and condition, we computed both the median and the standard deviation of the *x* positions of the center of the handle, relative to the *x* position of the center of the target, at the time of contact (or attempted contact). Repeated measures ANOVAs did not reveal a significant difference between the handle-visible and invisible conditions for either the median contact position ($F_{1,7} = 1.12$, $P = 0.33$) or the standard deviation of the contact positions ($F_{1,7} = 0.63$, $P = 0.45$). To test whether the variability in median contact positions across participants differed between conditions, we used the Levine test for homogeneity of variances. This test indicated that the inter-participant variability was greater in the handle-invisible condition than in the handle-visible condition ($F_{1,14} = 12.94$, $P = 0.003$). Thus, removing vision of the handle significantly increased contact location variability between participants, but not within participants. Figure 2b shows two participants' gaze fixation locations, relative to the target position (normalized across the five targets), in the handle-visible and handle-invisible conditions. Each cross represents the location of gaze at the end of a saccade bringing gaze to the target; fixations related to all contact attempts are shown. As illustrated by these two participants, no obvious differences were observed between fixation locations in successful hits (gray crosses) compared to mishits and misses (black crosses). Paired *t* tests, based on median values computed for each participant, failed to show a significant difference in either the *x* or *z* gaze positions between the handle-visible and invisible conditions ($P = 0.79$ and $P = 0.06$, respectively). These results suggest that the accuracy of gaze shifts to the targets was similar in the two conditions.

We also computed, for each participant and condition, the median peak contact force generated in correct hits. No reliable differences in peak contact force was observed between the handle-visible and invisible conditions ($F_{1,7} = 0.56$, $P = 0.48$). This suggests that participants could quite accurately predict contact time in the handle-invisible condition. Had participants poorly predicted when contact would occur in the handle-invisible condition, we might have expected differences in contact force between the two conditions.

Hand trajectories

Figure 3a shows representative hand paths produced in the handle-visible and handle-invisible conditions by two participants. In the handle-invisible condition the u-shape of the hand path between successive targets was more pronounced and the hand retracted further between targets, resulting in longer hand paths from target to target. A repeated measures ANOVA, based on the median hand path distance between successive correct hits computed for each participant and condition, confirmed that the distance between target contacts was greater ($F_{1,7} = 11.7$, $P = 0.011$) in the handle-invisible condition ($M = 13.17$ cm, SD = 2.13 cm) than in the handle-visible condition ($M = 10.97$ cm, SD = 1.65 cm). (Note that these means and standard deviations are based on the median values provided by each participant.) Similarly, the time interval between correct target contacts, also based on median values, was significantly greater ($F_{1,7} = 27.1$, $P < 0.001$) in the handle-invisible condition ($M = 483$ ms, SD = 39 ms) than in the handle-visible condition ($M = 429$ ms, SD = 49 ms).

Consistent with the observation that the hand retracted further between hits in the handle-invisible condition, the hand tended to approach the near surface of the target at a more perpendicular angle in the handle-invisible condition. To examine the angle of approach, for every successful hit, we computed the angle of the vector from the center of the handle at contact to the center of the handle at the location where the displacement between the two center locations first decreased to less than 3 cm. Similarly, to examine the angle at which the hand retracted from the target, we computed the angle of the vector from the center of the handle at contact to the center of the handle at the location where the displacement between the two center locations first exceeded 3 cm. The gray lines in Fig. 3b illustrate the median approach and retraction angles for each participant in the handle-visible and invisible conditions. The thick black lines illustrate the mean approach and retraction angles averaged across participant medians. A repeated measures ANOVA revealed that the approach angles in the handle-visible and invisible conditions were significantly different ($F_{1,7} = 14.0$, $P = 0.007$). However, no significant difference was observed in the retraction angle ($F_{1,7} = 5.11$, $P = 0.058$). Thus, participants approached the target at an angle more perpendicular to the contact surface in the handle-invisible condition compared to the handle-visible conditions. The more perpendicular approach used in the handle-invisible condition may be a compensatory strategy employed to increase the chances of contacting the object surface, given increased uncertainty in the position of the

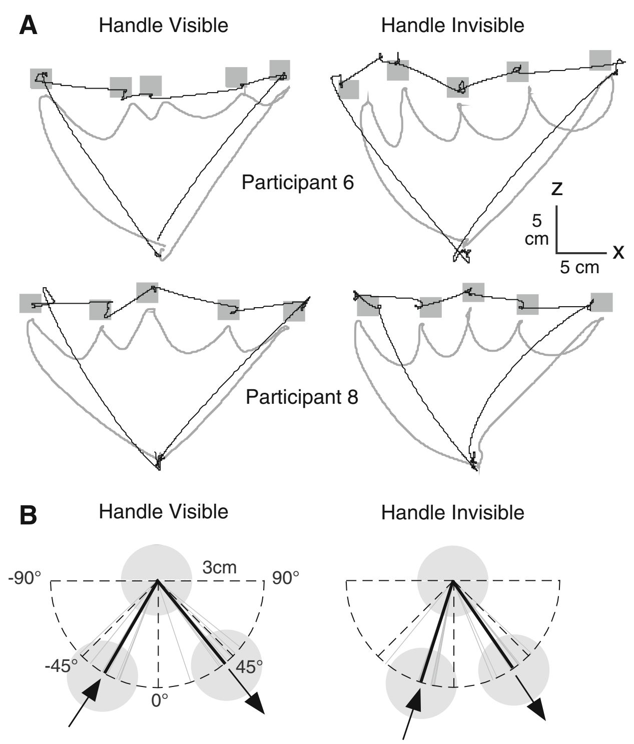

Fig. 3 Hand paths. **a** Top views of hand (*gray traces*) and gaze (*black traces*) paths from single trials with the handle-visible and invisible shown for two participants. The *dark gray squares* represent the locations of the five targets. **b** Handle approach and retraction angles in the handle-visible and invisible conditions. In each *panel*, the *top gray circle* represents the position of the handle when first contacting the target. The *bottom left circle* shows the average location (based on participant medians) of the handle when the center of the handle approached within 3 cm of the center of the handle at the contact position. The *bottom right circles* shows the average location of the handle when the center of the handle retracted 3 cm from the center of the handle at the contact position. The *thin gray lines* show the approach and retraction angles for each participant (based on medians), and the *thick black lines* show the average approach and retraction angles. The *arrows* represent the direction of handle movement

handle in the *x* direction. A similar suggestion related to approach angles has been made in the context of grasping (Smeets and Brenner 1999, 2001; Cuijpers et al. 2004; Kleinholdermann et al. 2007).

Temporal coordination of gaze and hand movements

Figure 4a shows cumulative frequency distributions of gaze arrival and exit times, relative to the instance the handle first contacted the target in both the handle-visible (top panel) and handle-invisible (bottom panel) conditions. Separate distributions are shown for each of the five targets where each distribution includes all correct hits from all participants. Repeated measures ANOVAs, based on participant medians, revealed significant effects of target on both gaze arrival and exit times in both the handle-visible and handle-invisible conditions ($P < 0.001$ in all four cases). Gaze arrived earliest at target 1 and exited latest from target 5 (see Fig. 4a). The early gaze arrival at target 1 was presumably related to the relatively large amplitude hand movement between the start position and the first target. After contacting target 5, participants were required to bring the handle back to the vicinity of the start position, but there was no time constraint imposed on this movement. This may explain the relatively late gaze exit from target 5. Figure 4a also suggests that gaze tended to arrive increasingly later from targets 2 to 5, and tended to exit increasingly later from targets 1–4.

To examine differences in the timing of gaze arrivals and exits across conditions, we focused on the middle three targets (and thus disregarded the early gaze arrivals and late gaze exits observed for targets 1 and 5, respectively). Figure 4b shows separate cumulative frequency distributions of gaze arrival and exit times for correct hits involving the middle three targets for each participant and condition. Repeated measures ANOVAs based on median gaze arrival and exit times computed for each participant failed to reveal a difference in gaze arrival times ($F_{1,7} = 2.56$, $P = 0.15$) between the handle-visible ($M = -208$ ms, SE = 15 ms) and handle-invisible ($M = -248$ ms, SE = 20 ms) conditions. However, gaze exits in the handle-visible condition ($M = 106$ ms, SE = 7 ms) were slightly, but significantly later ($F_{1,7} = 16.5$, $P = 0.005$) than in the handle-invisible condition ($M = 87$ ms, SE = 8 ms). As can be visually appreciated in Fig. 4b, gaze arrival times varied considerably across participants (due to the fact that different participants moved their hand between successive targets at different speeds). In contrast, there was far less variability in gaze exit times across participants. This finding is consistent with our previous results showing that, in a block stacking task, changes in movement duration affect gaze arrival, but not gaze exit times (Flanagan and Johansson 2003).

Catch hits

To assess how haptic contact information influenced the timing of gaze shifts from one target to the next, we included occasional trials in which we removed force feedback when one of the middle three targets was contacted. If gaze shifts from one target to the next were reactively triggered, based on haptic contact cues, we would expect to see a delay in the gaze exit time referenced to the instance of contact. In our analysis of contact events not involving force feedback, we only included correct hits and will therefore refer to these events as catch hits (as only a handful of catch mishits and catch misses were observed, these attempts were not analyzed). Figure 5 shows, for both the handle-visible and handle-invisible conditions, cumulative frequency distributions of gaze arrival and exit times,

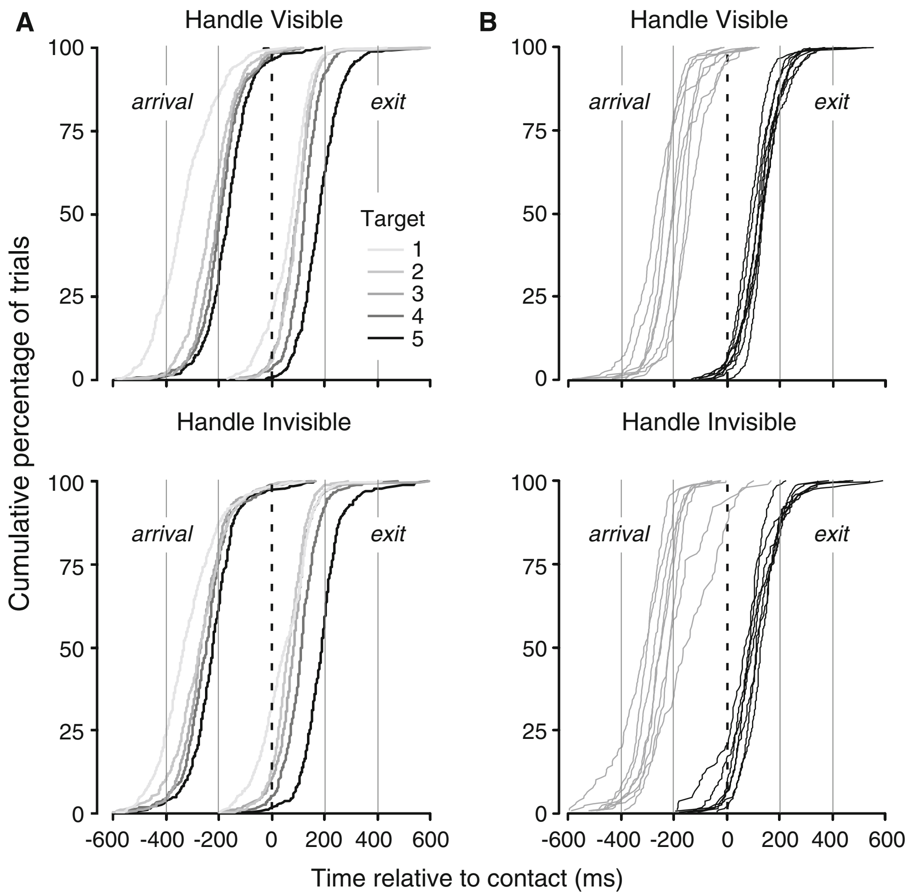

Fig. 4 Gaze arrival and exit times. **a** Cumulative distributions of gaze arrival and exit times, relative to contact, for each target and for the handle-visible and invisible conditions. Each distribution combines data from all participants. **b** Cumulative distributions of gaze arrival (*gray curves*) and exit (*black curves*) times for each participant and condition. Data from targets 2, 3 and 4 have been pooled together in these plots

relative to contact for correct hits and catch hits. The data for correct hits were taken from the middle three targets only so that they could be directly compared with the catch hits. Each distribution shows data from all participants.

In both the handle-visible and invisible conditions, the distributions of gaze exit times that occurred before 130 ms after contact were very similar for correct hits and catch hits (Fig. 5; dashed vertical lines mark 130 ms after contact). This accounted for approximately 65 and 75% of catch contacts in the handle-visible and invisible conditions, respectively. Thus, in the majority of catch hits, gaze exits were not delayed. However, gaze exits that occurred later than 130 ms after contact appeared to be delayed for catch hits in comparison to correct hits. In the handle-visible condition, the median gaze exit times of gaze exits occurring >130 ms after contact were 284 and 153 ms for catch hits and correct hits, respectively. In the handle-invisible condition, late gaze exits in catch hits were even more delayed. The median gaze exit times of gaze exits occurring >130 ms after contact were 632 and 160 ms for catch hits and correct hits, respectively. Kolmogorov–Smirnov tests verified significant differences between the distributions for correct hits and catch hits in both the handle-visible ($Z = 3.48$, $P < 0.001$) and handle-invisible ($Z = 1.63$, $P = 0.01$) conditions (Note that the correspondence between late exit times in correct hits and delayed exits times in catch hits was clearly evident at the level of individual participants. Participants who shifted their gaze away from the target relatively soon after contact exhibited few, if any, delayed exits on catch hits. Participants who generated later gaze shifts exhibited more delayed exits on catch trials.). In contrast to gaze exits, in both the handle-visible and invisible conditions, the distributions of gaze arrival times for correct hits and catch hits were quite similar. This suggests that the delayed gaze exits, seen in approximately 30 and 40% of catch hits in the handle-invisible and visible conditions, respectively, were not associated with delayed gaze arrivals.

In catch hits in the handle-invisible condition, participants received no sensory feedback indicating that the target was contacted, and in 60% of these events, they made one or more corrective hand movements in an attempt to contact the target before continuing. In contrast, in catch hits in the handle-visible condition, participants received visual information indicating that the target was contacted even though tactile feedback related to contact force was absent. That is, they saw the circle representing the handle move through the target. In this condition, participants made corrective hand movements in an attempt to hit (or re-hit) the target in only 15% of the catch contacts.

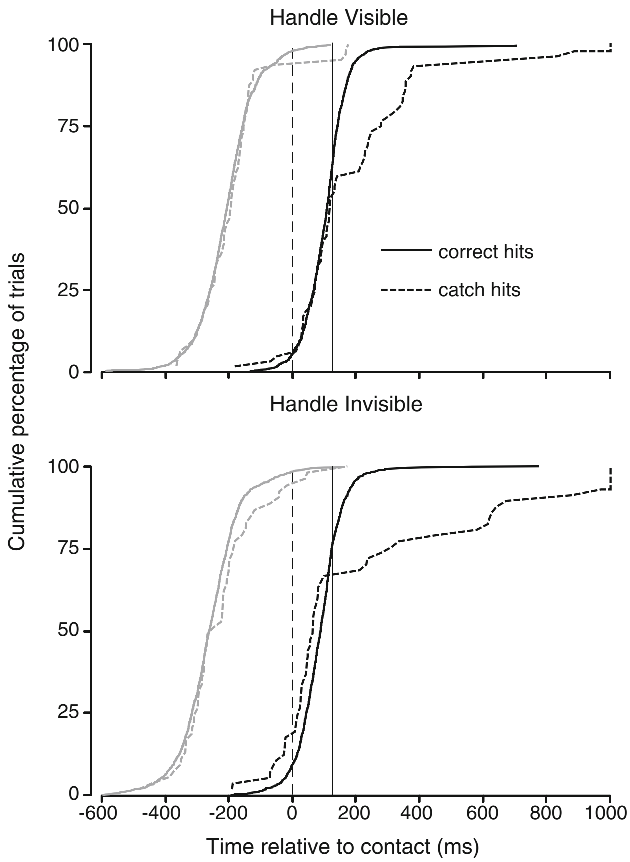

Fig. 5 Catch hits. Cumulative distributions of gaze arrivals (*gray traces*) and exits (*black traces*), relative to contact, for correct hits and correct catch hits in both the handle-visible and invisible conditions. The *vertical solid lines* marks 130 ms after contact. Exit times greater than 1,000 ms were set to 1,000 ms

Discussion

We have shown that in our sequential target contact task, participants fixated each target and, on average, maintained fixation at the target until shortly after it was contacted by the grasped handle. Similar gaze behavior was observed regardless of whether visual feedback representing the position of the handle was present or absent. This indicates that the mechanisms responsible for generating gaze shifts away from the target can be driven by non-visual feedback loops; i.e., they do not require visual feedback about the relative positions of the handle and target.

In order to examine whether gaze shifts away from the target were triggered reactively in response to sensory feedback related to contact force, we included occasional catch hits in which contact force was removed. In both the handle-visible and invisible conditions, we found that the timing of the majority of gaze exits in catch hits was similar to the timing of gaze exits in correct hits involving force feedback. However, in 40% of catch hits in the handle-visible condition and 30% of catch hits in the handle-invisible condition, gaze shifts were delayed. These percentages corresponded to the percentages of correct hits, in the two conditions, in which gaze shifted later than 130 ms after contact. Our interpretation of these results is that saccadic gaze shifts between targets are generally proactive, but can be delayed if prior to saccade initiation there is a mismatch between predicted and actual tactile (and possibly proprioceptive) feedback related to contact. In object manipulation tasks, mismatches between predicted and actual tactile feedback result in corrections to fingertip forces within about 100 ms (Jenmalm and Johansson 1997; Jenmalm et al. 2000; Johansson and Birznieks 2004; Johansson and Westling 1984, 1988). Our results suggest that such mismatches can also influence task-specific eye movements within about 130 ms. Using an eye movement countermanding task, Akerfelt et al. (2006) demonstrated that a tactile stimulus can be an effective saccadic stop signal. These authors report that participants can inhibit saccades to a visual target 90–140 ms after receiving a vibratory stimulus to the hand. Our results indicate that the absence of an expected tactile signal can inhibit or delay the execution of saccades within a similar time frame. Note that these saccade inhibition times are considerably shorter than the 200 ms required to generate a saccade toward the location of a tactile (vibratory) stimulus applied to the hand (Groh and Sparks 1996). Gaze exits that were delayed in catch hits were far more delayed, on average, in the handle-invisible condition than in the handle-visible condition. These results indicate that although the absence of expected tactile feedback can suppress the saccade to the next target (if it has not yet been launched), in many cases visual feedback can be used to confirm contact and allow eye movements in the sequential task to continue within 100–200 ms.

An alternative explanation for our results is that 40 and 30% of all gaze shifts in the handle-visible and invisible conditions, respectively, were reactively triggered based on sensory feedback related to contact forces. As a consequence, the same percentage of gaze shifts would be expected to be delayed in catch hits. Although we cannot rule out this explanation, we note that all of our participants exhibited approximately normal distributions of gaze exit times, which included a substantial proportion of exit times that occurred less than 130 ms after contact (Fig. 4b). Therefore, we suggest that, in general, participants employed a proactive gaze strategy rather than a reactive strategy in which gaze shifts are triggered in response to tactile or visual signals signaling that contact has occurred. That is, we suggest that the sensorimotor system launches each saccade in anticipation that the target will be contacted, i.e., the goal of that current action phase will be attained. This conclusion agrees with a number of previous studies of gaze behavior in object manipulation tasks showing that, in many instances, gaze shifts away from a given contact location around the time, or even before, contact occurs (Ballard et al. 1992; Epelboim et al. 1995; Johansson et al. 2001; Land et al. 1999; Flanagan and Johansson 2003). Nevertheless, it should be emphasized that, in general, the timing of gaze shifts is task-specific. Although the gaze shifts observed in our task appear to be predictive, reactive gaze shifts would be expected under some task conditions. For example, in a version of our task in which the five targets disappear prior to hand movement onset, manual performance is impaired and reactive gaze shifts are seen (unpublished observations).

Neggers and Bekkering (2001, 2000) examined the coordination of gaze and hand movements in visually guided pointing, using a task in which participants were required to point to a reach target. During the reach and while gaze was directed to the reach target, a second gaze target could be presented and participants were instructed to shift their gaze to this target as quickly as possible. These authors found that participants could not execute a saccade away from the reach target until around the time the fingertip arrived at the reach target. Such gaze anchoring was seen both when vision of the hand was available and when it was not (Neggers and Bekkering 2001). On average, gaze shifted to the second gaze target about 50 ms after the finger contacted the reach target. Saccadic reaction time was found to be about 220 ms, indicating that the preparation of these saccades was initiated about 170 ms before the fingertip contacted the reach target (Neggers and Bekkering 2001). These results indicate that, as in the task that we have examined, gaze shifts were planned predictively rather than reactively in response to sensory information confirming that the movement goal was achieved. These findings also suggest that an internal signal directly related to the arm movement command, rather than a visual signal related to the image of the moving arm, can be used to program the oculomotor system and that this signal can only be effectively exploited up until 170 ms before the predicted target contact. This interpretation agrees with our results showing that removing vision of the handle has little effect on the timing of gaze shifts between targets and that these shifts are generated predictively.

Previous studies of reaching to visible targets have shown that removing vision of the hand only slightly degrades pointing accuracy, provided the visual information about the initial hand position is available (Jeannerod 1988; Prablanc et al. 1979, 1986). Consistent with this observation, our participants were generally successful at performing the sequential target contact task in the handle-invisible condition, in which they received visual feedback about the initial position of the handle, but were unable to see the handle position during the task. However, because they received haptic feedback when contacting the visible targets, they effectively received visual feedback related to handle position at contact. That is, at contact, the viewed location of the target could provide an estimate, based on haptic information, of the position of the handle (with an offset in the z position and some uncertainty in the x position).

We have suggested that one reason why gaze may be directed at target contact locations, during contact events, is so that central visual information related to these events can be obtained and compared to predicted information (Flanagan et al. 2006; Johansson et al. 2001). Just as predicted and actual tactile information related to contact is compared in object manipulation tasks (Jenmalm and Johansson 1997; Jenmalm et al. 2000; Johansson and Westling 1984, 1988), so too may predicted and actual foveal information be compared. If mismatches between predicted and actual sensory information are detected, the sensorimotor system can take corrective actions and update representations of objects in the environment so as to improve future control and prediction (Flanagan et al. 2006; Johansson and Flanagan 2007; Land et al. 1999; Wolpert and Flanagan 2001; Wolpert and Ghahramani 2000; Wolpert et al. 2001). By directing gaze to contact locations, during contact events, the sensorimotor system may also be able to maintain spatial and temporal alignment among different sensory signals. Because contact events give rise to salient sensory signals from multiple modalities (including tactile, proprioceptive, auditory and visual signals) that are linked in time and space, these events provide an opportunity for intermodal alignment of sensory signals (Flanagan et al. 2006; Johansson and Flanagan 2007).

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