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Coordinating one hand with two eyes: optimizing for field of view in a pointing task

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Abstract

We previously found that subjects switched 'ocular dominance' as a function of horizontal gaze direction in a reaching task [Vision Res. 41 (14) (2001) 1743]. Here we extend these findings to show that when subjects pointed to targets across the horizontal binocular field, they aligned the fingertip with a vertical plane located between the eyes and the target. This eye–target plane gradually shifted from aligning with the left eye (leftward targets) to between the two eyes (intermediate targets) to the right eye (rightward targets). We suggest that this occurs to optimize eye–hand alignment towards the eye with the best overall field of view.

Keywords: Eye–hand coordination; Eye position; Binocular vision

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1. Introduction

When discussing eye–hand coordination, one generally considers how the hand aligns with *the* eye in various perceptual-motor tasks (Binsted, Chua, Helsen, & Elliott, 2001; Henriques & Crawford, 2002; Johansson, Westling, Backstrom, & Flanagan, 2001). However, this ignores the fact that healthy individuals have *two* eyes. Here, we consider how eye–hand alignment is selected in binocular, frontal-eyed organisms like the human; which eye do we coordinate the hand with, and how is this affected by visual target direction?

1.1. Eye–hand alignment

Recent studies (Engel, Flanders, & Soechting, 2002; Johansson et al., 2001; Land & Hayhoe, 2001; Neggers & Bekkering, 2000, 2001) have found a close link between the movements of the arm and eyes. When asked to saccade to a new target while making a pointing movement to a previous target, these studies reported that subjects were unable to saccade to the new target until the completion of the pointing movement suggesting a 'yoking' of the eye and hand. Fisk and Goodale (1985) similarly found that saccades latencies, measured during a reaching task were longer when preceding a contralateral arm movement than for an ipsilateral one, which again suggest a 'yoking' effect. Neggers and Bekkering (2001) proposed that this effect is useful for the visual-motor system in coordinating reaching movements toward visually fixated targets. The importance and intimacy of such eye–hand alignment are emphasized in the finding that pointing performance breaks down when the eye is not aligned with the target (Bock, 1986; Henriques & Crawford, 2000), and in the finding that when pointing toward a target, rather than directing the finger on a vector from the shoulder to the target, subjects tend to intersect the finger on an imaginary line formed from the target to the eye (e.g., Henriques & Crawford, 2002).

1.2. Binocular vision

In their recent study, Henriques and Crawford (2000) examined eye–hand alignment with one eye patched, but

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suppose we ask how binocular viewing affects such tasks? Which eye is chosen for the purpose of eye–hand coordination?

The ocular dominance theory suggests that one eye is chosen over the other (Porac & Coren, 1976), whereas the cyclopean eye theory proposes that objects are seen as if from a central point between the two eyes (Ono & Barbeito, 1982; Wells, 1792). However, the classical cyclopean theory suggests that in order for objects to be *perceived* as aligning between the cyclopean eye and target, near targets—like the pointing fingertip—should align with one gaze line or the other (Wells, 1792). So the question remains: which eye is selected for eye–hand coordination?

Several classical studies have looked at this question for straight-ahead targets (Coren & Kaplan, 1973; Crider, 1944; Miles, 1930; Porac & Coren, 1976). Our goal was to see how this selection process is influenced by the horizontal position of the eyes and target. In a recent paper we showed that in a reaching and grasping task subjects aligned the hand with either their left *or* right eye depending on gaze position (Khan & Crawford, 2001). Subjects consistently aligned the hand to the left eye for leftward targets and the right eye for rightward targets although the crossover point from the left to the right eye varied across subjects. This seems to imply that when the brain has to align targets with an eye, it chooses one eye and furthermore bases this choice on eye position.

1.3. Goal of the current study

One potential weakness of our previous study is that the paradigm was not particularly natural. Subjects were asked to reach out and grasp a ring, but then bring it back to the head without allowing it to cross the gaze line. Moreover, the geometry and explicit visual cues of the task may have influenced the subject's forced-choice decision. The purpose of the current study therefore, was to test to see if a similar effect occurs for an implicit eye–hand alignment task, i.e., pointing towards illuminated targets in an otherwise dark room (Fig. 1).

This task has a number of advantages over the reaching and grasping task used in our previous study; (a) it is less likely that naive subjects will be aware of the aim of the test, (b) pointing is more natural in the sense that no special instructions are required beyond ''point at the target'', and (c) whereas our previous study used a forced choice (left or right eye) paradigm, with pointing, one can quantify a motor output that could potentially fall anywhere between (or beyond) alignment with either eye. The question is—would subjects continue to show a preference (as measured by eye–hand alignment) for the left eye in the left visual field, and the right eye in the right visual field?

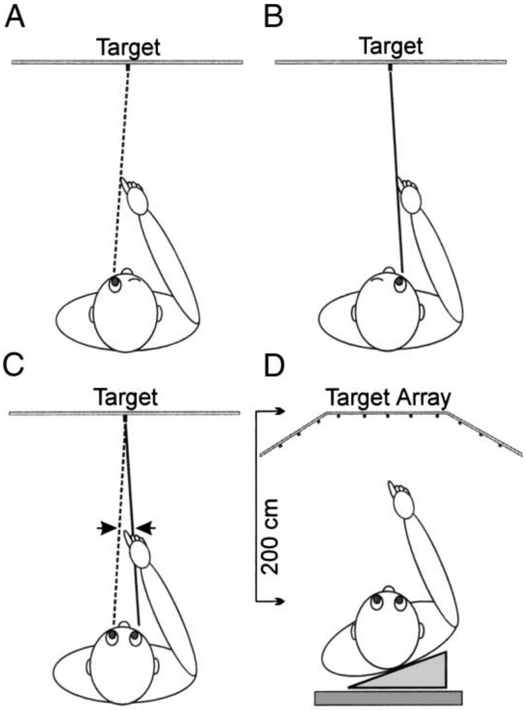

Fig. 1. *Schematic of pointing task*. During the monocular tasks, subjects pointed to each target with either the left or right eye closed thereby aligning the target with the left (A, dotted line) or right (B, solid line) eye. (C) Arm measurements during binocular tasks will be compared to monocular eye–target lines (A and B) to determine how the binocular eye–target lines are formed at each angle, which could occur anywhere between left and right arrows shown in C (when target is straight ahead, our results show that the finger is positioned at a point between the two eyes). (D) *Experimental apparatus*. Targets at 10° intervals from 50° left to 50° right were located on a semi-hexagonal shaped board at a distance of 200 cm from the subjects' eyes. A wedge-shaped board (depicted) was placed between the subject and the seat to rotate the torso by 20° left in order to facilitate pointing.

2. Methods

2.1. Subjects

Ten right-handed subjects gave informed consent to participate in the experiment, seven of which were naïve to the purposes of the experiment. Their ages ranged from 20 to 46 years ($M = 25.6$, SD = 6.8).

2.2. Apparatus

Subjects were seated in a chair fitted with a bite bar to restrict head movements. The head was immobilized in order to simplify the geometry of target–hand–eye alignment, which changes considerably when the head is allowed to move (Henriques & Crawford, 2002). A wedge shaped piece of wood was placed behind their backs so as to rotate their bodies 20° toward the left. This was done to center the mechanical range of the arm near the center of our forward visual display (Fig. 1D).

Eleven targets (light emitting diodes, LEDs) were placed at eye level 200 cm in front of the subject at 10° intervals from 50° left to 50° right along a semi-hexagonal shaped board, well within the binocular field (Henson, 1993). Within our study, four subjects were unable to see the target located at 50° right (this subject-to-subject variability is apparently due to the shape of the nose), however all other targets were visible to all subjects. The centre target located at 0° was aligned to the right eye. Subjects were asked to point (with their finger) to targets as they were illuminated. Arm orientations were recorded using the three-dimensional (3-D) search coil technique (Henriques, Klier, Smith, Lowey, & Crawford, 1998; Tweed, Cadera, & Vilis, 1990). A dual 3-D arm coil was attached laterally to the upper right arm. To encourage precise measurements of pointing angles from the upper arm coil, the subject wore an elbow brace, which discouraged the elbow from bending.

In addition, experiments were repeated on four of the 10 subjects wearing a 2-D scleral eye coils in their right eye to confirm that subjects were accurately fixating the pointing targets. This was important to establish, because our previous studies have shown the deviations between gaze and target influence pointing performance (Henriques & Crawford, 2000; Henriques et al., 1998). To confirm that this was not occurring, we compared the angle of fixation of the right eye to predicted fixation angles (target angles). Across subjects and target directions (40° left to 40° right), the average error (distance from target direction) was only 0.86. Larger errors were made at the extreme target directions of 50° off center (average distance from target angle was 5.06°). For all targets, when comparing target angle to ocular fixation angle, our data gave a correlation coefficient (across subjects) of $r = 0.984$. Thus, errors in gaze fixation were unlikely to have had a significant effect on pointing performance, particularly for the central range of targets where, as we shall see, the main effect of switching the target–finger–eye alignment occurred.

2.3. Procedure

Subjects performed two sets of experiments, one in complete darkness and one in dim light in order to compare the effect of visual feedback of the arm. Fig. 2 shows typical trajectories of the arm and the eye during the experiment. Since subjects vertically undershoot (i.e., point below) pointing targets in the dark (see Henriques & Crawford, 2000; Henriques et al., 1998 for details), their performance was not guided by 'covering' the target with the finger. In each experiment, subjects completed a set of five blocks, in which targets were presented randomly (each target was presented twice resulting in 22 target presentations per block). Each LED was illuminated for 3.5 s with an interval of 1.5 s between presentations. As each target was illuminated, the subject was required to look directly at it, point to it and press a button with the other hand when they were certain that they were pointing correctly to the target. During both binocular and monocular trials, subjects were only asked to point toward the LED and were not given any instructions to align their fingertip with the gaze line.

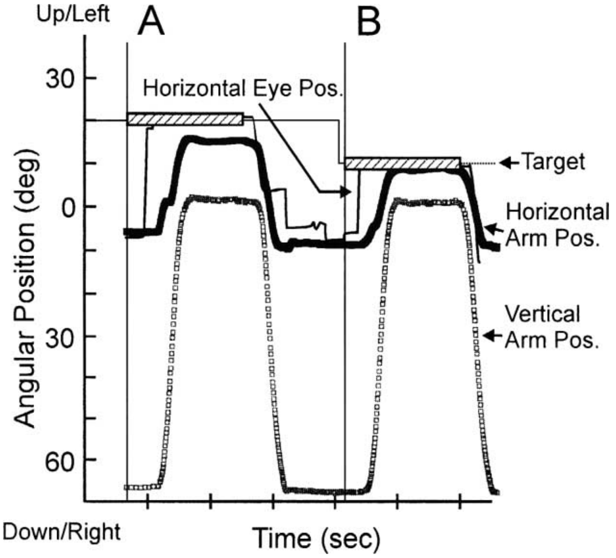

Fig. 2. *Sample trajectories from a typical movement during task performance.* Horizontal and vertical arm positions as well as the horizontal eye position are plotted over time for two consecutive trials (A and B). Trajectories were extracted from coil signals from the upper right arm and the right eye with targets presented at 20° (A) and 10° (B) left. 0° in the *y*-axis is defined as being horizontally aligned with the right eye for horizontal eye and arm position signals. When the target was illuminated, the subject fixated on it and brought the arm up from resting position to point at the fixated target. After the target was extinguished, the subject returned the arm to resting position and fixated on the next illuminated target.

Following the set of five blocks, subjects repeated a set of three monocular control blocks twice. This was done first with the left eye patched and then with the right eye patched. All monocular blocks were performed in dim light regardless of whether the binocular blocks were performed in darkness or dim light. Targets during the monocular trials were presented in sequential order (50° left to 50° right). These controls were done to see if subjects would consistently align the fingertip with the unpatched eye, and to establish a baseline for measuring alignment in the binocular task.

2.4. Data analysis

Arm position angles obtained during monocular trials were used to obtain eye–target lines for the unpatched eye. In order to test which eye subjects aligned their fingertip with, we compared the eye–target lines obtained during binocular trials to those obtained during monocular ones. Arm position angles were calculated by transforming quarternions obtained through the 3-D arm coils (Tweed et al., 1990). The use of this method for recording arm orientation has been described elsewhere (Henriques et al., 1998). In brief, reference recordings were taken while each subject pointed toward the central target with full visual feedback of the target and arm. Every other upper arm orientation is then measured as a rotation from that reference orientation. So long as the arm is held fully extended (like a rigid cylinder), upper arm orientation is monotonically related to the location of the fingertip in space (which is why subjects were required to wear the arm brace). Again, it is known that subjects undershoot pointing targets vertically in the dark, and that this shows no particular correlation with horizontal target position (Henriques & Crawford, 2000; Henriques et al., 1998). Therefore, we confined our data analysis to horizontal arm orientation. In other words, this study only considers target–hand–eye alignment in the horizontal plane as viewed from above.

2.5. Predicting arm positions

To test if subjects' fingers actually intersected the eye–target line for the monocular trials, we calculated the required angular positions of the arm based on the rotational centres of the eyes, head and arm relative to one another using an Optotrak 3020 digitizing and motion analysis system (unfortunately, this apparatus was not yet available when the main results of this study were collected). Additionally, we measured the distances and angles between the centres of rotation for the eyes (1.3 cm behind the surface of the eye), head and arm (the arm was assumed to be fully extended, i.e., following a straight line from shoulder to fingertip) while subjects were seated in the apparatus. Based on these values, we predicted the angular arm position from angular eye position using the geometric equations described in Henriques and Crawford (2002).

3. Results

3.1. Monocular pointing: theoretical predictions and controls

Fig. 3A shows the average (across subjects) *predicted* arm orientation for pointing with the finger aligned between the targets (50° left to 50° right) and the left eye (squares) versus the right eye (triangles). On average, these two lines were shifted relative to each other by 1.949°. This shows quantitatively the expected angular shift in the upper arm between aligning the finger with the left eye as opposed to the right eye. Qualitatively, the data follow the same pattern as the predicted curves (Fig. 3C shows data obtained from trials in the dark), with data from the right eye-patched condition showing a shift toward alignment with the left eye (squares) and left eye-patched data aligning with the right eye (triangles). On average, (across targets and subjects), the shift between the right and left eye was ±1.06°, not significantly different from the predicted shift (±0.97°). Pointing variability for each subject across targets was quite small; the average standard errors for the left and right eye were 0.34 (range = 0.25–0.43) and 0.4 (range = 0.23–0.63), respectively. But note that when plotted here in terms of absolute arm angle as a function of target angle, these shifts are small and difficult to see compared to the overall change in arm angle between the targets. Therefore, to focus on the effect of interest, we first re-plotted these predictions, but normalized with respect to the 'cyclopean eye' i.e., the mean point between the two lines. Fig. 3B shows the data plotted according to this convention, which we will adopt from this point onwards. This highlights the relative differences between the expected pointing performance for aligning with the left versus right eye.

Do subjects adopt such alignment strategies when asked to point monocularly (with one eye patched) and with visual feedback of the target and arm in dim light? Fig. 3D shows the actual data (average ± SE), normalized in the same fashion as described above. We further quantified this by calculating correlations between the raw (un-normalized) arm position data and the predicted data, which showed slopes and correlations of 1.03 ($r = 0.9960$) and 1.02 ($r = 0.9961$) for the left and right eye, respectively. Furthermore, these predicted arm orientations accounted for almost all the systematic variability (most subjects undershot leftward targets and overshot rightward ones) found in the obtained arm orientations for the left ($R^2 = 0.9921$) and right ($R^2 = 0.9922$) eye. The R^2 values also confirm that subjects were holding their arms fully extended (with the help of the arm brace for the elbow) during the pointing trials. Thus, with monocular patching, subjects aligned horizontal pointing with the unpatched eye, providing our first result and the controls for our main experiment.

3.2. Binocular pointing

We hypothesized that when both eyes were viewing, subjects would align the target with either their left or right eye depending on gaze direction (Fig. 1). Fig. 4 shows normalized measured arm orientation versus target direction (averaged across all subjects) for experimental binocular trials (dashed lines) plotted over the left and right monocular control trials (left—squares, right—triangles) from the last section. Data are plotted separately for trials during dark (Fig. 4A) and dim light (Fig. 4B) conditions.

As one can see, in the binocular condition, subjects aligned their finger with the left or the right eye

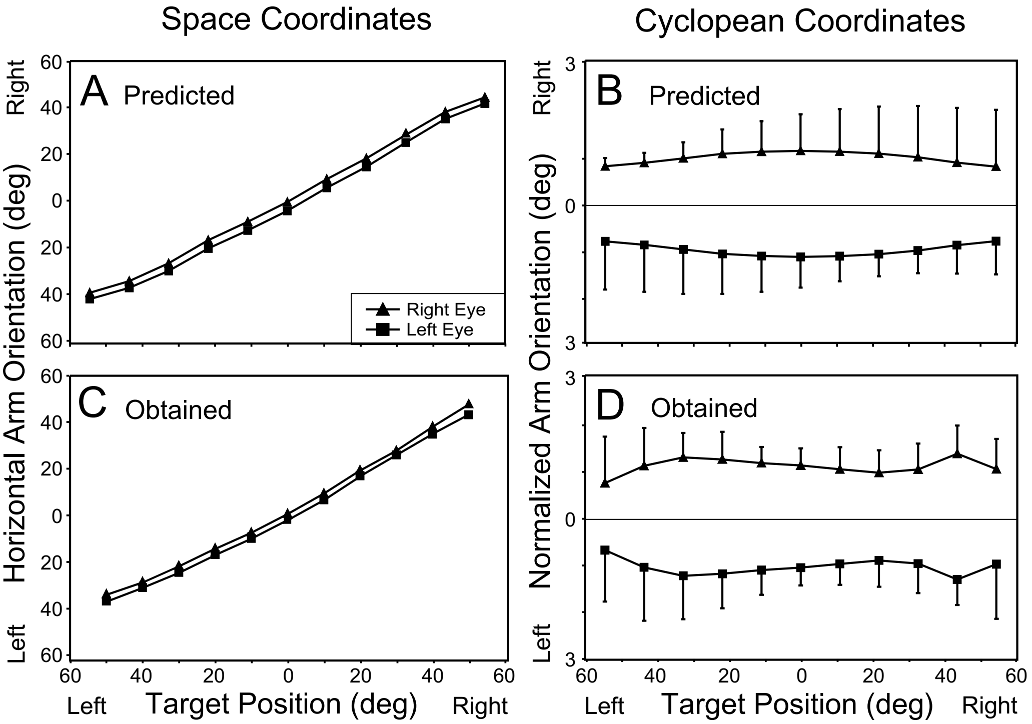

Fig. 3. *Predicted and obtained control pointing positions.* (A) Raw predicted pattern presented in space coordinates. Predicted monocular arm orientations for left (squares) and right (triangles) eye monocular trials are shown across all target positions and all subjects. (B) Normalized predicted pointing positions shown in cyclopean coordinates, i.e. data from the left and right eye are presented relative each other. The data were transformed as follows: first the mean pointing position (representing the cyclopean eye) at each target was calculated by averaging the horizontal pointing position for the left and right eye. Values for the right and left eye were subsequently subtracted from this average pointing position for each target. (C) Raw obtained pattern shows the obtained arm orientations for each target averaged across subjects for left (squares) and right (triangles) eyes. Data is shown for trials performed in the dark. (D) Data from panel C was transformed in a similar manner to B. Standard error bars in Fig. 3B and D show inter-subject differences.

depending on target direction. On average, during leftward targets, pointing directions during binocular viewing matched that for the left eye control task (i.e., finger intersected the left eye–target line), whereas the reverse was true for the rightward targets. The average transition between the left and right eye alignment during dark trials took place at 5° right of center. This reversal between alignment with the left and right eye across the binocular field was not as clear during trials in dim light as it was during trials in the dark, and the shift occurred more gradually for these trials (Fig. 4B).

To quantify whether binocular pointing responses were similar to pointing responses aligned with one eye more than the other, we performed t-tests for each target direction between the binocular tasks and each monocular control task. In the dark paradigm, for targets left of the central target, subjects' pointing responses during binocular trials did not significantly differ from those during left eye control trials but were significantly different from right monocular control trials ($p < 0.05$). The reverse was true for targets rightward of the centre target: binocular pointing responses were significantly different from left but not right monocular trials. In dim lighting, the transition in aligning the finger with the left eye to aligning with the right eye is not as clear as in the dark condition and is significant only for targets leftward of (not including) 20° left and rightward of 30° right ($p < 0.05$).

3.3. The crossover shift

The gradual nature of the *average* left to right eye alignment shift in Fig. 4 (across subjects) could have occurred because the shift is gradual in individuals, or because different people shift at different points. In order to study this matter more closely, we translated the data for each subject so that the crossover point of each subject (point at which the line fit to the data crosses 0 on the y-axis) was centered at the 0° target on the x-axis. We then averaged this data across subjects. Fig. 5 shows this average crossover shift across subjects for both dim and dark light paradigms. The crossover from the left to the right eye occurred relatively quickly (within 20°) for trials that took place in complete darkness but took longer for trials in dim light (within 45°).

Further, this crossover shift within subjects could have resulted from two different patterns behavior within individual subjects: (i) either data points were

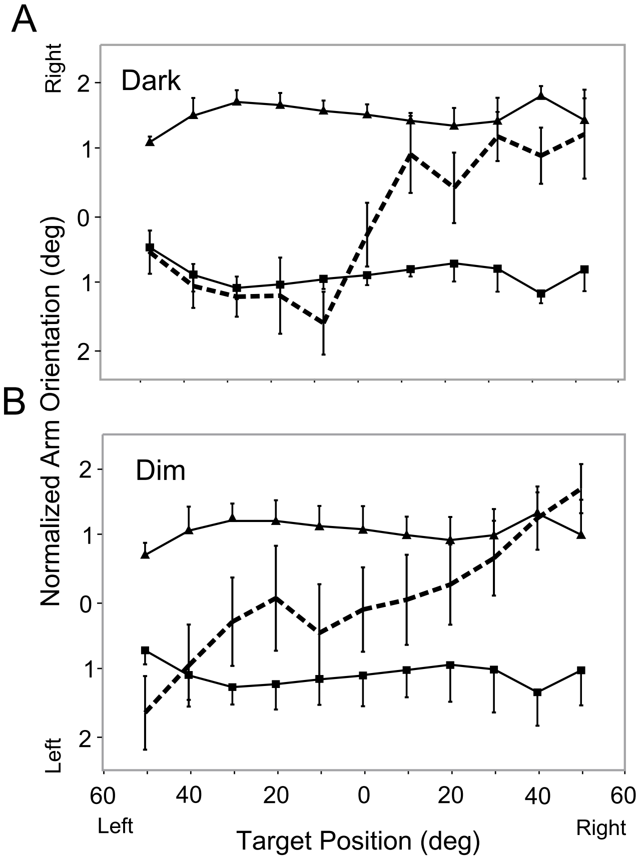

Fig. 4. *Binocular pointing positions across subjects.* Mean normalized pointing positions for 10 subjects plotted as a function of target position during trails performed in: (A) dark and (B) dim light with the right arm. The normalized pointing positions for binocular (dashed lines), left monocular (solid lines with squares) and right monocular (solid lines with triangles) trails are shown. The standard error bars in all three sets of trials depict the horizontal pointing error for each target position across subjects (see legend of Fig. 3).

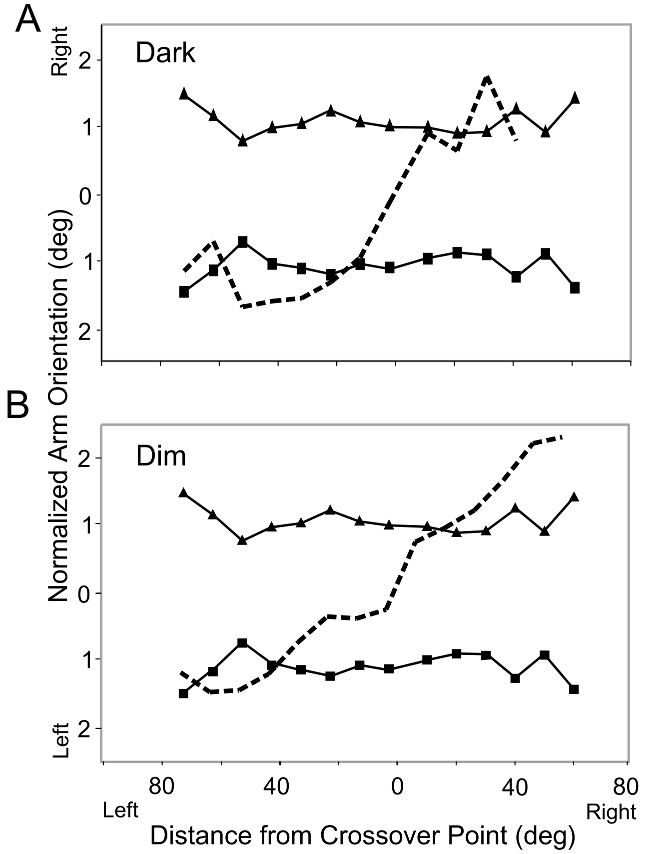

Fig. 5. *Average translated crossover shifts.* Average data across all subjects translated so that each crossover point for each subject took place at 0° center horizontally for dark (A) and dim light (B) paradigms. Shift from pointing using the left eye to pointing using the right eye was more abrupt during the dark paradigm (taking place over approximately 30°) compared to the dim paradigm (approximately 40°).

bimodal, always aligning with either the left or right eye with an equal chance of the finger aligning with the left or right eye at the crossover point, or (ii) the data formed a unimodal distribution which gradually shifts from aligning with the left eye for leftward targets, to aligning with a point halfway between the two eyes at the crossover point, to aligning with the right eye for rightward targets.

To discern which of the two patterns the data follow, we compiled frequency histograms of the raw data points at each translated target value for all subjects. Fig. 6 shows the results for both the dark and the dim light paradigms for distances of 50° left, 10° left, 0° center, 10° right and 50° right of the crossover point (from Fig. 5). Contrary to our initial expectations, the data showed little tendency to cluster bimodally about the left and right eyes (vertical dashed lines). The data suggest rather, that there was a gradual shifting of a roughly unimodal distribution, where the subject aligns the target entirely with the left eye at extreme leftward targets to aligning the target with somewhere between both eyes at centre targets to the opposite eye at extreme rightward targets.

4. Discussion

Our data suggest that when pointing toward eccentric targets, subjects tended to align their fingertip closer with the eye–target line of one eye—that with the better field of view i.e., not just the foveal view of the target itself, but also the surrounding workspace. When looking straight ahead, the information about the visual image entering from the two eyes to the brain is almost equal, but this changes when gaze is directed away from the centre. For example, consider the situation where the eyes are looking at a target at the extreme left while the head faces forward. In this case, a large part of the input from the contralateral eye would be a rather non-informative view of the nose. Therefore, it makes sense that if one is to align the hand with one eye, to align it with the eye with the better field of view, which may be very important for future actions e.g., pointing to

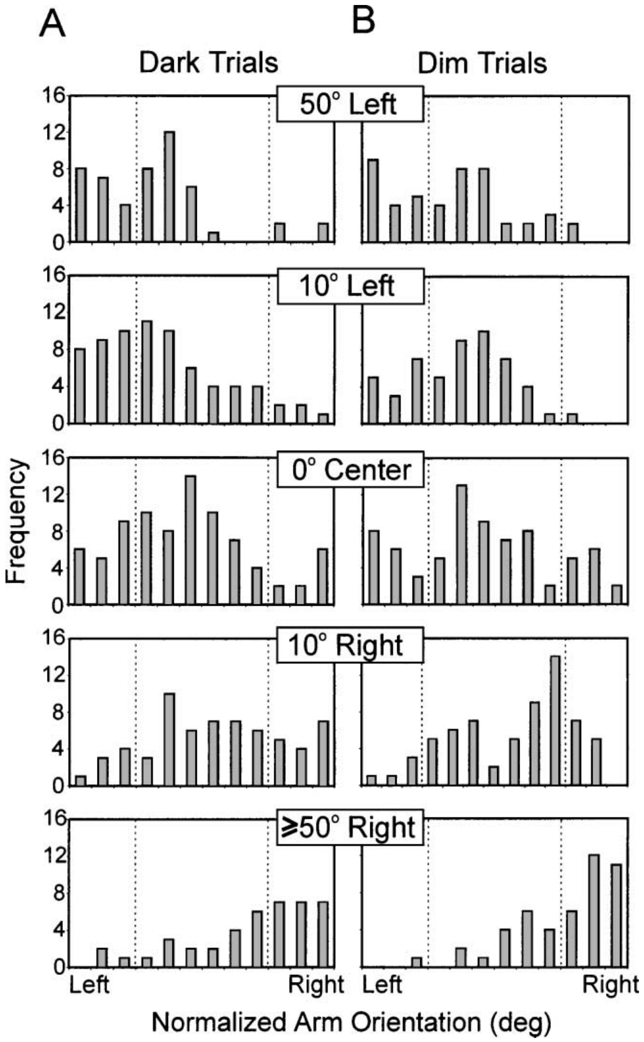

Fig. 6. *Frequency histograms of raw data points across translated targets.* Data points were taken from all subjects during dark (column A) and dim (column B) paradigms. The two vertical dashed lines in each histogram represent the location of the left and right eye normalized pointing positions. Frequency histograms for translated target values for binocular trials (see Fig. 5) for distances of 50° left, 10° left, 0° centre, 10° right and 50° right from the crossover point. The 50° right figure consists of data points from 50°, 60° and 70° right as there were not sufficient data points at the 50° right position.

relevant targets that are not currently foveated. However, our data suggest that this choice comes into play not just at extreme gaze angles but also well within the binocular range.

Surprisingly, the data obtained from trials in dim light were not as clear-cut as those obtained for the dark trials; the switch over from aligning with the left eye to aligning with the right eye was more gradual and variable in the dim trials. This may be caused by interference from visual feedback of the hand during pointing and might suggest that an eye-switching algorithm is built into the motor control system for eye–hand coordination but vision allows for more flexible strategies.

Based on our hypothesis that the brain chooses the 'dominant' eye with the best field of view (Khan & Crawford, 2001), we had expected a bimodal distribution to the binocular data where each peak would be located near the monocular control data for either eye. Instead the data seem to imply that the brain chooses a more continuous shift, weighted toward the eye with the better field of view. Thus, for straight-ahead targets, our results are consistent with the results of Mapp and Ono (1999) who found that the pointing had aligned physically between the cyclopean eye and the target (they did not test peripheral targets). Clearly, our pointing data did not align with the classical cyclopean eye for more peripheral targets, although our results would seem consistent with the idea of aligning the hand between the target and a shifting cyclopean eye (Mansfield & Legge, 1996).

Although the latter statement is physically true on its face, and the motor aspects of our results are clear, it is difficult to use our data to draw conclusions about the cyclopean eye or any other mechanism of perceptual judgment. The cyclopean eye, as originally conceived (Hering, 1868/1977; Ono, 1979; Wells, 1792) is the head-centred reference point for the judgment of visual direction. It does not necessarily follow from this that in motor control, subjects would necessarily try and align the hand with this perceptual reference point. For example, somewhat paradoxically, Well's classical experiments show that the fingertip would have to physically align with the gaze line of one eye in order to be *perceived*—from that eye, as aligning with the line between the cyclopean eye and the target. Thus, a sensorimotor strategy that produces switching between the two eyes, either continuously or discontinuously, does not conflict with this perceptual theory. The bottom line is that since we did not ask our subjects where they perceived the direction of their fingertip, our results do not comment directly on perceptual judgments, relative the cyclopean eye or otherwise.

Although our subjects tended to prefer aligning the hand with one eye or the other (at least at extreme gaze angles), it is unlikely that the information entering the brain from the other eye had no influence. For example, Servos, Goodale, and Jakobson (1992) have shown that binocular vision is superior to monocular vision in reaching and grasping tasks. Specifically, they showed that among other factors, binocular reaching and grasping movements were faster, had shorter latencies and higher peak velocities than the same tasks performed with monocular viewing.

4.1. Algorithms for eye–hand alignment

How can one reconcile these different views of perception and eye–hand coordination? One possibility is that even if the brain synthesizes information from the two eyes and refers this to a central, cyclopean point, it also 'gates' the amount of information entering from the two eyes depending on gaze direction; with the purpose of optimizing the field of view at all times. Such gating could be based on the relative visual angle of the target in the two eyes, an internal sense of the position of the eyes, or a calculation of visual direction of the target based on both the retinal stimulus and eye position sense. This might be a good compromise between completely suppressing information from one eye and always equally gating information from the both eyes. This dynamic shift between the relative importance of the two eyes has been shown in other studies as well (Erkelens & Van Ee, 1997; Mansfield & Legge, 1996). Thus, the idea here is that the hand is guided more by vision from one eye than the other. This visual gating mechanism is consistent with the results of our previous study (Khan & Crawford, 2001) but does not explain why in the current study, our subjects showed a continuous, unimodal shift in pointing direction that was actually more crisp in the dark.

A second possibility that could explain our data is some kind of purely motor algorithm that coordinates the hand toward the eye with the best field of view. This may be related to studies which suggest that the hand is somehow 'yoked' to the eyes (Fisk & Goodale, 1985; Neggers & Bekkering, 2000, 2001). Again, the yoking of the hand to one eye or the other could be based on visual information, eye position information, or a combination of the two, all of which is available throughout the cortical transformations for eye–hand coordination (Andersen, Snyder, Bradley, & Xing, 1997; Anderson & Zipser, 1988). Another factor may be the choice of which arm is used, which appeared to influence ocular dominance in our previous study (Khan & Crawford, 2001). In any case, the hand would be weighted toward the eye with the better field of view through this motor algorithm, with 'gating' secondary to this or not necessarily occurring at all. Although our study cannot evaluate which processes occur, it is possible that both processes are employed to some degree.

In conclusion, this paper shows that eye position had an effect on the alignment of the finger with the eye–target line revealing a shift between the left eye and the right eye that depended on horizontal target direction. We propose that the eye–hand coordination system uses a strategy that optimizes for the current field of view. This may involve eye-position dependent gating of information or a motor strategy, or a combination of both processes. However, at this point, it remains completely unclear whether similar optimization principles hold for purely perceptual tasks (like binocular rivalry), and if so, whether this is subserved by the same underlying mechanisms.

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