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Eye position sense contributes to the judgement of slant

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Abstract

We measured monocular judgements of the slant of a cube face while varying eye position in the absence of stereoscopic and external lighting cues. Errors were found to be small, only 10% on average of the cube's eccentricity. Two factors appear to have contributed approximately equally to this error: an underestimate of cube slant as seen by the eye and an underestimate of eye position. When prism adaptation altered the sensed eye position, the pattern of slant judgements changed to reflect the altered sense of eye position. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Extra-retinal signals; Eye position; Perception; Prism adaptation; Slant

1. Introduction

To judge the slant of an object's surface with respect to oneself in the absence of visible reference cues as to its orientation with respect to one's body, two critical pieces of information must be assessed: the orientation of the surface with respect to the eye and the eye's gaze direction (Fig. 1). While most studies of slant perception are based upon this fundamental assumption, very little is known about how the extra-retinal sense of eye position contributes to the monocular judgement of surface slant.

In contrast, the relative contribution of various visual cues to the perception of surface slant has been studied extensively. Binocular vision, for example, resolves object slant through the pattern of differences between the two retinal images, and informs on the direction of gaze. Backus, Banks, van Ee, and Crowell (1999) recently determined the contribution of eye position and horizontal and vertical disparities to stereoscopic slant perception. Non-stereoscopic surface cues such as shading, reflected highlights, and texture gradients have also been studied (Mammassian & Kersten, 1996; Todd, Norman, Koenderink, & Kappers, 1997). The geometric visual cues that contribute to depth/slant judgement were examined by Attneave (1972), who found a tendency to perceive the slant of geometric objects depicted in depth to be less than their actual values.

In the present study, we investigated the role of eye position and slant with respect to the eye in the monocular judgement of surface slant. To accomplish this, stimulus objects (glowing cubes) were viewed monocularly at various eccentric positions and slants.

2. Methods

2.1. Centre vantage point

We investigated the perception of surface slant by measuring judgements of the orientation of three-dimensional textured cubes. Fig. 2 is a schematic representation of the experimental apparatus as seen from above. Subjects were seated at a table in a dark room in which the walls and tabletop had a black matt finish. The subjects' heads were restrained in a headrest, and their left eyes were patched. A three-dimensional glowing cube (luminance = 2 cd/m^2) was displayed at eye level, randomly turned between 45° left and 45° right (0° being parallel to the table edge) around a vertical

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axis. The cubes were lit from within to avoid the allocentric reference cues that would be provided by external lighting. The cube's front face was diamond-shaped, as the cube was displayed tilted 45° on its side. The centre cube was 56 cm from the table edge and measured 11.5 cm across the front face (cube dimensions: 8 × 8 × 8 cm).

The subjects' task was to reorient the cube so that the cube's front face seemed parallel to the table edge at which they were seated (fronto-parallel when viewed from the centre, Fig. 2). The task was accomplished by turning a featureless and not visible disk that was mechanically coupled to the vertical rod that supported the cube. Cube orientations were measured with an Optotrak camera/infrared emitting diode system (Northern Digital). Ten reorientations were performed at each cube display position. This was repeated at five horizontal cube display positions, center, ± 15°, and ± 30°. Ten subjects, who were paid for their time, performed this experiment.

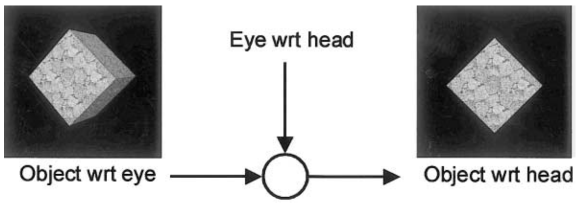

Fig. 1. Realignment of the eye's view of a cube by a sense of eye position. The cube on the left illustrates the eye's view of a cube that is to the subject's left: the *object with respect to* (*wrt*) *eye*. If one knows how far the eye is turned (*eye wrt head*), one can compute the cube's orientation with respect to the head (*object wrt head*) and thus one's self; in this case, that the cube's front surface is facing directly forward.

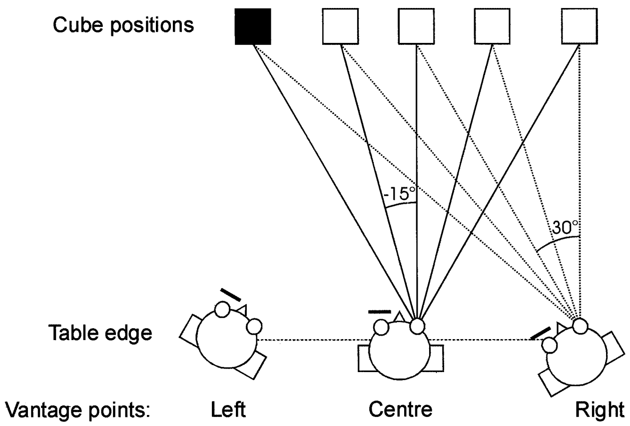

Fig. 2. Experimental set-up as viewed from above. The subject is seated at one of three vantage points (left, centre or right) and views a cube at one of five display positions (squares). In the right and left vantage points, both the head and body are turned 30° either to the right or to the left with respect to the table edge. The subject's task is to reorient the cube so that its front face parallels the table edge (dashed line) at which the subject is seated. The left eye is patched, and the subjects view the display only through the right eye. A headrest restrains the subject's head.

2.2. Prism adaptation

To confirm the dependency of slant judgements on the internal sense of eye position, we modified the sense of eye position by adapting subjects to Fresnel prisms that rotated the visual world 15° leftwards about the prism axis. The 10 min prism adaptation task involved the subjects' wearing the prisms and using their feet, while standing, to manipulate wooden blocks on the floor into various shapes like rectangles and triangles; an adaptation of Craske's method (Craske, 1967; Crawshaw & Craske, 1976; Craske & Crawshaw, 1978). We developed such a procedure as a result of our finding in a preliminary study that prism adaptation using visually guided pointing at the cubes with the arm had no effect on slant judgements—we found, instead, that the pointing arm had adapted its position sense. The standing adaptation procedure was more effective in adapting the sense of eye position presumably because of the additional error cues provided by vestibular and whole body proprioceptive signals. To verify adaptation of the extra-retinal eye position signal, the subjects verbally directed the positioning of a dot of light in the dark to where they felt was their eye's straight-ahead position. This measurement was repeated 20 times.

Ten subjects performed the cube reorientation task, from the central vantage point before and after prism adaptation, in both cases without prisms. Five-minute repetitions of the prism adaptation task were interspersed between cube display positions to prevent loss of adaptation.

2.3. Varied vantage points

To differentiate slant judgement errors that were related to the eye's gaze direction from those related to the eye's view of the cube's slant, we had subjects view cubes from different vantage points. In the experiment described in Section 2.1, gaze direction and the desired orientation of the cube did not vary independently, i.e. when the eye looked 30° left, the task was always to orient the cube at a 30° angle to the line of sight. Thus, to separate gaze direction and slant relative to the line of sight, five subjects also viewed the display from vantage points 30° to the right and left, i.e. without turning the head with respect to the body, the subject was turned ± 30° with respect to the table edge (see Fig. 2). The instruction to the subject was the same at each vantage point: to reorient the cube's front face to parallel the table's front edge.

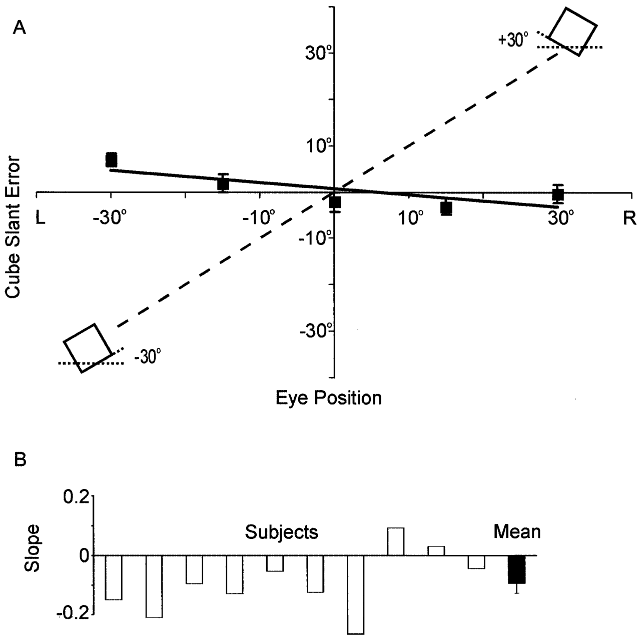

Fig. 3. (A) Cube slant errors with respect to the table edge as a function of eye position for a single subject seated at the centre vantage point. The mean error is calculated from 10 trials at each cube display position, error bars indicating the standard error at each point. Slope (solid black line) = -0.13. The dashed line indicates the slope that would occur if subjects had no sense of eye position, i.e. the subjects turned the cube inwards so that the front face was perpendicular to the line of sight at all cube display positions. The large hollow squares indicate the direction of this error with respect to the table edge: positive error when the cube's front face is turned to the cube's right and negative error when the cube's front face is turned to the cube's left. Perfect slant judgements would result in the data points aligning with the abscissa. (B) Slope values of all 10 subjects (white), with mean slope (black), -0.09 ± 0.03 S.E. ($P<0.05$, Student's t-test). For comparison, a slope of 1 would occur if subjects had no sense of eye position.

2.4. Two cubes

The varied vantage points paradigm, however, introduced a potential third source of error. To perform the task, a judgement of the orientation of the table with respect to the head is required. Errors in this assessment could not be separated from errors due to eye position or cube slant with respect to the eye. A simple experiment was designed, therefore, which required only the assessment of eye position in the head and cube slant relative to the line of sight. Instead of one cube displayed at five positions, two cubes were shown: one in the centre position, and one at one of the four peripheral positions. The new task was to reorient the central cube to match the peripheral cube's orientation in space. The peripheral cube's orientation was varied randomly between approximately $-45°$ and $+45°$.

Subjects typically made repetitive saccades between the two cubes. Thus, eye position could have been assessed either from an estimate of eye position at each cube or from an estimate at the central cube position together with an estimate of the eye's displacement. The experiment did not attempt to differentiate between these two possibilities. Ten subjects performed 10 reorientations for each of the four peripheral cube display positions.

3. Results

3.1. Centre vantage point

Fig. 3A plots a subject's slant judgement error as a function of eccentricity for the centre vantage point. At each eccentricity, subjects made small errors that were highly consistent across trials, visible in the small standard error bars at each cube display position. The mean error varied with the cube display position and thus the eye position required to view it. To examine this dependence, a linear fit was applied to the data, and the slope was examined. Veridical performance would yield data along the abscissa (slope = 0). Failure to compensate for eye position would yield data along the dashed line (slope = 1) as a subject, not knowing the direction of his gaze, would attempt to face the cube towards gaze normal at each position. In contrast to a value of one, the mean slope across the 10 subjects was small, -0.09 ± 0.03 standard error ($P<0.05$, Student's t-test), close to veridical performance, (Fig. 3B), translating to an error of approximately 3° at 30° eccentricity. Thus, subjects were able to compensate for eye position quite accurately.

3.2. Prism adaptation

Prism adaptation (see Section 2) had a clear effect on sensed eye position and slant judgement. All subjects displayed a leftward shift (mean 5.5° ± 2° SE, $P<0.05$) in their felt straight-ahead eye position post-adaptation, demonstrating the successful realignment of the sensed eye position (Fig. 4). The degree of adaptation (approximately 37%) was comparable to previous studies (Craske, 1967; Crawshaw & Craske, 1976; Craske & Crawshaw, 1978; Harris, 1965; Kohler, 1964). Prism adaptation also induced an error in slant judgements (Fig. 5); on average, the 10 subjects responded as though the cube face had been rotated leftwards about the body axis, as indicated by a downward y-intercept shift (mean 2.4° ± 1° S.E., $P<0.05$) from pre- to post-adaptation (Fig. 5B).

3.3. Varied vantage points

In the first experiment (Section 3.1), the source of the error is ambiguous. It could be due to an error in sensed eye position, an error in judging the cube's slant from the eye's perspective, or a combination of the two. This is because, when viewing a cube at an eccentric position, say 30° right, gaze direction and the slant of the cube with respect to the eye vary together. To distinguish between these two possible sources of error, the first experiment was repeated from three vantage

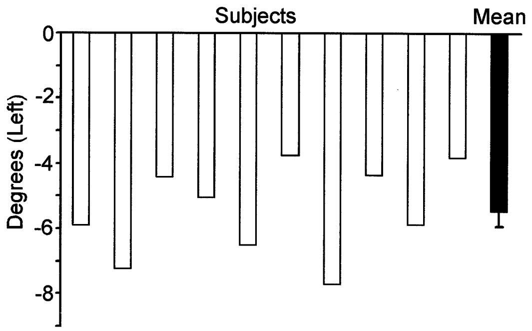

Fig. 4. Effects of prism adaptation on the felt straight-ahead eye position of all 10 subjects. Each (white) bar represents the mean change in the sensed straight-ahead eye position of a single subject. Mean straight-ahead eye position change across subjects (black bar on the right) was 5.5° leftwards ± 2° S.E. ($P<0.05$, Student's t-test) following adaptation to Fresnel prisms that rotate the visual world 15° leftwards about the prism axis.

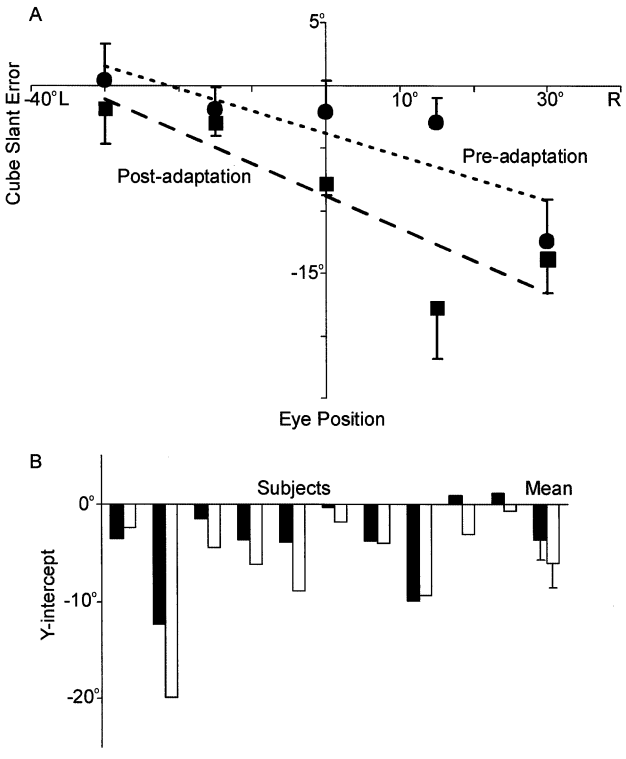

Fig. 5. (A) Effects of prism adaptation on the cube slant errors of a single subject seated at the centre vantage point. The mean error is calculated from ten trials at each position. Dotted line/circles: before prism adaptation. Dashed line/squares: after prism adaptation, without prisms. (B) The y-intercept for each subject, pre-adaptation (black) and post-adaptation (white). The mean change (black to white) was 2.4° ± 1° S.E., $P<0.05$ (Student's t-test).

points: from the centre (as before) and from the left and right (Fig. 2). Fig. 6 illustrates the average error of the five subjects. The interpolation surface shows that slant errors are dependent on both eye position and cube slant with respect to the line of sight. Consider first what happens when the ideal cube slant with respect to the eye is always zero (Fig. 6, dotted red line). This occurs when the subject is in the centre vantage point and views the cube in the centre display position, when the subject is in the left vantage point and views the cube in the left-most display position, and when the subject is in the right vantage point and views the cube in the right-most display position. In these cases, the error tends to become larger as the eye turns away from centre (Fig. 6, dotted red line); that is, subjects increasingly turned the cube face towards the centre. For example, when the subjects were viewing from the right vantage point and viewed the cube in the right-most display position, the subjects' gaze was 30° right, and the subjects mistakenly turned the cube so that its front face was turned to the cube's right. This line describes a positive relationship between error and eye position.

Additionally, for a constant straight-ahead 0° eye position, the subject's judgement of the cube's slant with respect to the table became more erroneous as its face turned away from gaze normal (Fig. 6, solid red line). As the cube face was turned away from gaze normal, subjects tended to turn it further away from gaze normal than was required (as if they were underestimating slant with respect to the eye). That is, when subjects viewed a cube whose front face was turned to the cube's right (e.g. when viewing the cube at the centre display position from the right vantage point, Fig. 2), the subject turned the cube too much to its right. The eye position 0° contour line (Fig. 6, solid red line) thus describes a positive relationship between error and cube slant relative to the line of sight for slants between approximately $-20°$ and $+20°$. At 20° to 25° from gaze normal, the cube slant-dependent error reached a peak and then appeared to decline.

To compare these data to those obtained in the experiments described in Section 3.1, the dashed red line in Fig. 6 shows where the data obtained from the centre vantage point experiment would lie. Looking at this line as a function of eye position would suggest a negative dependency of error on eye position. Yet the slope, as described above, is actually positive (dotted red line, Fig. 6). This difference is due to the interaction between these two sources of error, one of which, that of cube slant, appears to be highly non-linear.

When a quadratic polynomial surface, in both x (cube slant) and y (eye position), was fitted to the error data, the three largest coefficients were 0.19 x^2y, 0.15 xy^2 and -0.79 x^2y^2. The x^2y and xy^2 coefficients are positive and not significantly different in size ($P>0.05$ Student's t-test), suggesting that the errors are equally,

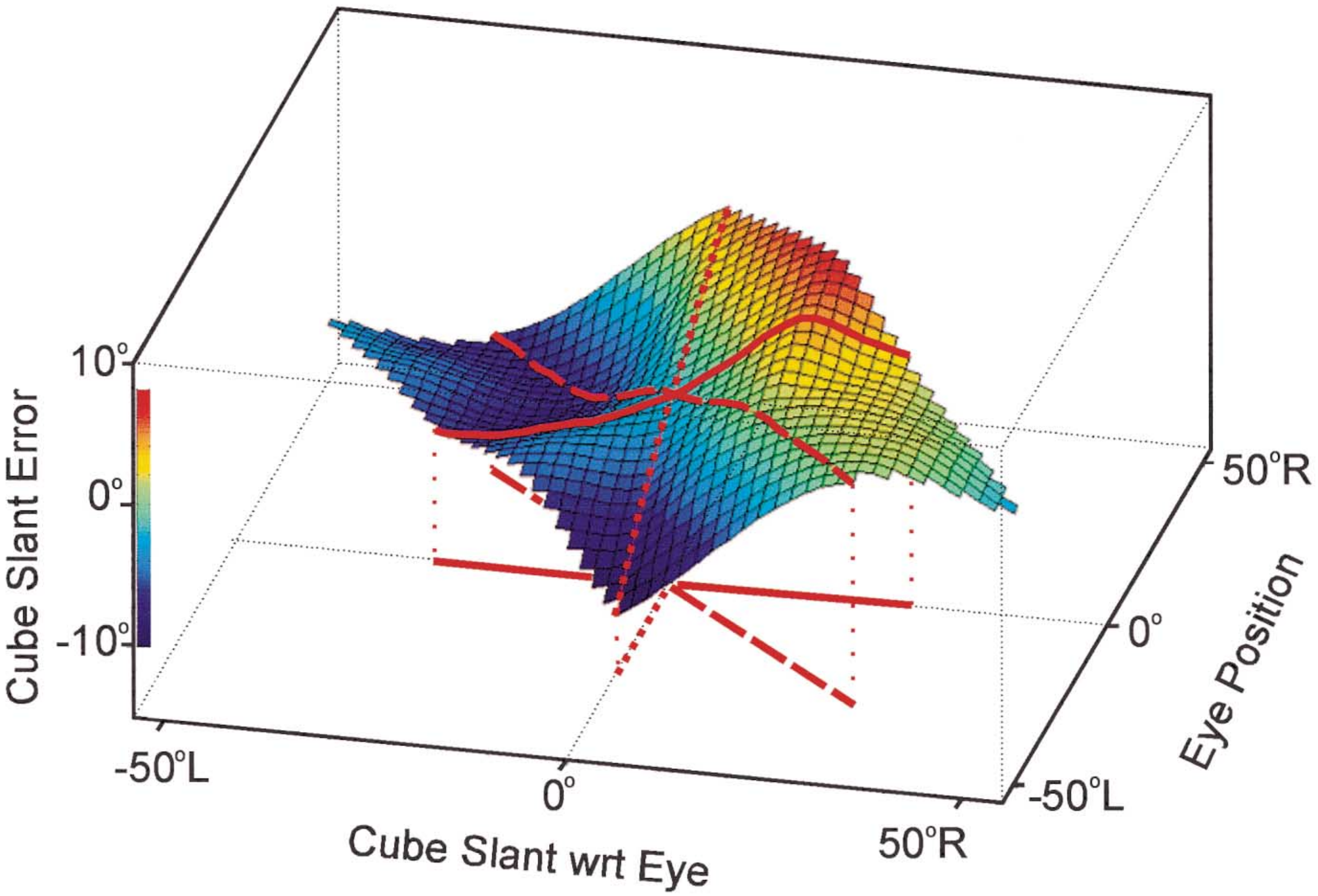

Fig. 6. Averaged slant errors of five subjects as a function of eye position and cube slant with respect to the eye. The surface was fitted to the data by cubic interpolation. The horizontal axis is cube slant with respect to the eye (the desired orientation of the cube), the axis in depth is eye position with respect to the head when looking at the cube centre, and the vertical axis is cube slant error with respect to the table edge. The colour bar next to the vertical axis relates the error value in degrees to a particular colour. Positive error occurs when the cube's front face is turned to the cube's right and negative error when the cube's front face is turned to the cube's left. Solid red line: 0° eye position contour line. Dotted red line: 0° cube slant contour line. Error is positively dependent on both eye position and cube slant. For comparison, the centre vantage point data of experiment 1, Fig. 3, would lie along the dashed red line.

but nonlinearly, dependent upon both the eye position sense and the cube slant with respect to the eye.

3.4. Two cubes

In the previous experiment, there were in fact three factors that could contribute to the error. Besides eye position and the judgement of cube slant with respect to the eye, there were, no doubt, errors in the subject's judgement of the orientation of the head with respect to the table edge. For example, when comparing the errors when the subject is at the left vantage point and viewing the cube in the left-most display position (Fig. 2) with those when the subject is in the right vantage point and viewing the cube in the right-most display position, both eye position and head orientation with respect to the table edge co-vary. In this last experiment, we eliminated this third error source by replacing the table edge landmark with a second cube (placed at the centre location in Fig. 2), and keeping head orientation constant. Here, the task was to turn the centre cube so that its front face appeared parallel, in space, to that of a cube placed in the periphery.

As before, we fitted a polynomial surface quadratic in both x (cube slant) and y (eye position) to the errors of all 10 subjects. Such a surface describes the dependence of slant judgment errors on both cube slant relative to the line of sight and eye position in the head. Fig. 7A displays this surface alongside the one-cube polynomial surface described in Section 3.3 (Fig. 7B). What it shows, perhaps to a more striking degree than in the one cube experiment, is the dependence of error on eye position.

As in the one cube experiment, for a constant cube slant with respect to the eye (e.g. the red dotted line describing 0° cube slant), the error is positive (red shading in Fig. 7) when matching to cubes viewed on the right and negative (blue shading in Fig. 7) when matching to cubes on the left. For example, if a cube at the left-most position (solid black in Fig. 2) was turned so that its front face was perpendicular to the line of sight (i.e. turned 30° to its left), subjects, positioned in the centered vantage point, would not turn the centre cube sufficiently to the centre cube's left. As before, this is consistent with the subject underestimating the eccentricity of the peripheral test cube, presumably because of an underestimate of eye position. The errors in the two-cube experiment were larger, visible in the colour gradient differences between Fig. 7A and B. For example, at cube slant/eye position coordinates of (15, 15) the two-cube error is 10.9°, while the one-cube error is 6.7°. At (− 15, 15), the two-cube error is 4.3°, and the one-cube error is − 2°. At (15, − 15), the errors are − 3.2° (two-cube) and − 2.2° (one-cube), and at (− 15, − 15), they are − 8.5° and − 6.6°, respectively. At each of these points, the two-cube surface describes errors approximately one and a half times larger than those of the one-cube surface.

The three largest coefficients for the polynomial describing the one-cube data were 0.19 x^2y, 0.15 xy^2, and − 0.79 x^2y^2. For comparison, the three largest coefficients for the polynomial describing the two-cube data were 0.44 x^2y, 0.15 xy^2, and 0.56 x^2y^2, the same as those of the one-cube but with one key difference: whereas the x^2y and xy^2 terms contributed approximately equally to the one-cube surface, the two-cube coefficients indicate that the x^2y term has a greater influence. This can be seen by comparing the pattern of colour gradients in Fig. 7A and B. In Fig. 7B, the green band (near-zero error) is diagonal and parallel to the diagonal edges of the surface, reflecting the equal dominance of the x^2y and xy^2 terms in the polynomial. In Fig. 7A, however, the green band is more horizontal than diagonal, reflecting the larger influence of the x^2y coefficient. The dominance of the x^2y term suggests that eye position contributes more to the error than cube slant relative to the line of sight and also that the interaction is non-linear.

4. Discussion

Our results show that humans can judge the slant of a surface when they must take eye position into account; only small errors in slant judgement are seen. The prism experiment confirmed that these slant judgements were indeed dependent upon an extra-retinal eye position signal.

The second goal of this study was to determine the origin of these small systematic errors. We wished to discriminate between slant judgement errors related to the eye's gaze direction and those related to the eye's view of the cube's slant, hence the varied vantage point experiment. The pattern of eye position dependent errors generated by subjects viewing from each of the three vantage points is consistent with an underestimation of eye position, results compatible with Morgan's (1978) findings in experiments examining the perceived location of objects in space.

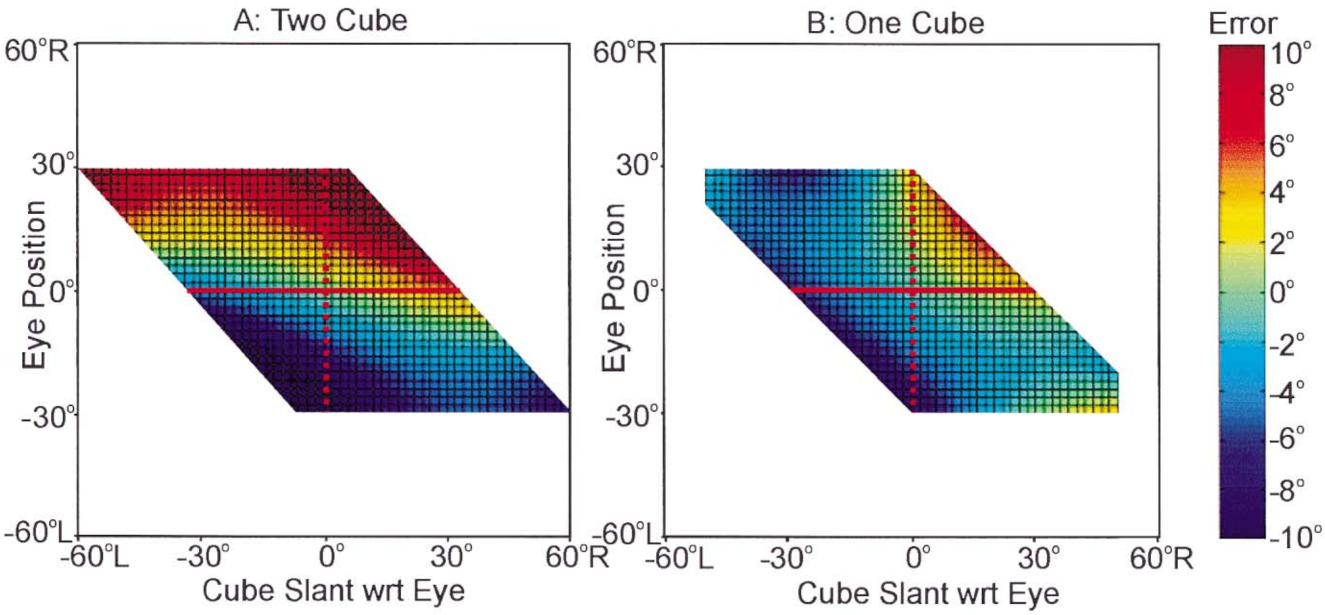

Fig. 7. Comparison of the data from the one- and two-cube experiments. Solid red line: 0° eye position contour line. Dotted red line: 0° cube slant contour line. (A) Two-cube data from 10 subjects; the vertical axis is eye position (when looking at peripheral display cube), and the horizontal axis is cube slant (of peripheral display cube). The colour bar on the right relates the error value in degrees (difference between peripheral display cube's orientation in space and that of the centre cube reoriented by the subject) to a particular colour. Positive error occurs when the centre cube's front face is turned to its left with respect to the display cube and negative error when the centre cube's front face is turned to its right with respect to the display cube. (B) For comparison, one-cube data from five subjects from Fig. 6.

As well, this experiment suggests that subjects tend to underestimate the slant of the cube relative to the line of sight. This error was smallest when the cube face was gaze normal, reached a peak when the cube was turned 20° to 25° from gaze normal, and then declined. Presumably this was because the orientation of a cube was easiest to determine from its geometry when its front face was gaze normal. As the desired cube orientation was turned away from gaze normal, it apparently became harder to determine the correct slant. The peak of the error occurred halfway to the next easily determined orientation of the cube, that when the front face was 45° from gaze normal (and the task could be performed by setting a cube vertex such that it appeared symmetric). Our observation of the tendency to underestimate slant with respect to gaze direction was similarly noted by Proffitt, Bhalla, Gossweiler, and Midgett (1995) when they discovered a tendency to perceive hills as steeper than in actuality. That is, their subjects overestimated the angle that hills make with respect to the flat ground plane; this is equivalent to underestimating the angle that hills make with respect to the frontal plane.

Our experiments suggest that the errors made when attempting to orient the cube face relative to the felt or remembered location of the table edge are similar in nature to the errors made when attempting to align two cubes with each other. A contributing factor in both appears to be an underestimation of eye position. It is somewhat puzzling that the errors produced when attempting to match two cubes, both visually defined, are larger than the errors produced when attempting to align to an unseen table edge. One possible explanation is that when comparing the slant of two cubes, one first computes the orientation of each with respect to oneself and then computes their relative orientation. The errors made in assessing the orientation of each cube would presumably be additive. The smaller errors seen when attempting to align a single cube to an unseen table edge could be due to the fact that the felt or remembered orientation of the table edge is not dependent on eye position.

Alternatively, a very different process may be involved. Consider, in the two-cube experiment, the situation in which the slant of the peripheral cube remains constant with respect to the eye, e.g. at a slant of zero (Fig. 7). If one compares the error at two eye positions, it clearly changes, from negative when the cube is to the left, to positive when it is on the right. Given that the slant of this cube with respect to the eye remains constant, this error would appear to be one that is solely related to eye position. However, eye position is not the only factor that changes in these two conditions. The slant of the central cube, the one the subject is attempting to align to the peripheral cube, changes as well. When looking, for example, 15° right, the subject should turn it 15° to the left and 15° to the right when looking 15° left. Thus, the change in error could, in part, be ascribed to this difference in the eye's view of the central cube.

This difference in the eye's view could in turn result in two types of errors. One is an underestimate of the eye's view of slant as described in the one cube experiment. The other is due to a memory-based comparison of the retinal views of the two cubes. Much current research shows that the recognition of previously seen three-dimensional objects is a function of the retinal projection of an object when it is seen again (Jolicoeur & Humphrey, 1998; Wallis & Bülthoff, 1999). Objects are well recognized if they are seen again with the same retinal projection, but poorly recognized if the retinal projection changes, even if such change is due to a simple translation of the object in space (Rock & DiVita, 1987). In the two-cube experiment, it is possible that the errors seen when attempting to align one cube to another are in part due to the visual system's over-reliance on the retinal view of these cubes and a mistaken attempt to match these views. This latter possibility could be examined through manipulations of the three-dimensional shapes of the objects to be matched.

We should note that the two-cube set-up leads to a compelling visual illusion. The illusion is best seen when a pair of identically oriented cubes is placed with first cube centred and its front face perpendicular to the line of sight and the second cube in a peripheral position. When one looks at these two cubes, they do not appear to have the same orientation in three-dimensional space. For example, the peripheral cube appears to be rotated too far to the right if it is on one's right. Like other visual illusions, knowing that the two cubes are oriented the same in space does not appear to change the magnitude of the illusion.

While many previous studies have explored the effects of viewpoint on object recognition (Jolicoeur & Humphrey, 1998; Rock & DiVita, 1987; Wallis & Bülthoff, 1999) or have examined cues contributing to the slant perceived while viewing objects centred in front (Attneave, 1972; Backus et al., 1999; Beck & Gibson, 1955; Mammassian & Kersten, 1996; Todd et al., 1997), very few studies have attempted to combine viewpoint and slant (Curthoys & Wade, 1995; Koenderink, van Doorn, & Lappin, 2000; van Ee & Erkelens, 1999). While it is phenomenally obvious that eye position must contribute to the accurate judgment of slant, our experiments are the first to confirm this. The small residual errors appear to be caused by approximately equal contributions from two factors: an underestimation of eye position relative to the head and an underestimation of cube slant relative to the line of sight.

Acknowledgements

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