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Effect of a disparity pattern on the perception of direction: Non-retinal information masks retinal information

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ABSTRACT

The direction of an object can theoretically be determined from the binocular disparity information alone. However, there is no certain empirical evidence for this. This study examines whether the binocular disparity information alters the perceived direction. Observers make an effort to rotate their eyes beyond their movable limit for a while before observing the display. This is done to alter the reliability of the eye position signal from proprioception and efference copy. The results show that the perceived direction changes according to the amount of disparity information in the stimulus.

1. Introduction

In order to locate an object in space, the brain uses the position information of the image on the retina and the position information of the eye relative to the head. The position of an object on the retina relative to the center of the retina generally[1] specifies its direction relative to the observer's direction of gaze because each retinal receptor signals light coming into the eye from one particular direction (retinotopic mapping). On the other hand, the position of the eye is determined from oculomotor proprioceptors in the muscles controlling the position of the eye and internal monitoring of the innervations sent to these muscles (efference copy).

Alternatively, the direction of an object can theoretically be determined from the binocular disparity information alone. Backus, Banks, van Ee, and Crowell (1999) derived the direction, a:

$$a \approx \arctan\left(\frac{\ln \mathrm{VSR}}{\mu}\right)$$

where μ is the angle between the lines of sight (vergence) and VSR is the vertical size ratio which is the ratio of the vertical angles that the object subtends at the two eyes (Gillam & Lawergren, 1983; Rogers & Bradshaw, 1993).

There is no certain empirical evidence for the use of vertical disparity in direction perception. If vertical disparity is used in the perception of direction, the apparent direction of a surface changes when vertical size disparity is displayed. Several investigators have reported anecdotally that no such change in apparent direction occurs (Frisby, 1984; Gillam & Lawergren, 1983; Ogle, 1950). Banks, Backus, and Banks (2002) pointed out that the observations in these earlier experiments were conducted in well-illuminated environments, with observers able to see their noses which clearly indicated the head-centric direction of the viewed surface. In the light of this, they conducted experiments in which any conflicting cue, such as the apparent position of the nose, was eliminated. The eye position-specified direction and the disparity-specified direction were independently manipulated and tested. They found no evidence that vertical disparity is used. Berends, van Ee, and Erkelens (2002) obtained similar results. They barely found any evidence that the perceived straight ahead direction was changed with the amount of vertical magnification in the stimulus, and only after the subject adapted to the vertical magnification for 5 min. They argued that vertical disparity is a factor in the calibration of the relationship between the eye position signals and the perceived direction. Vertical disparity and felt eye position were also shown to interact, for purposes of estimating stereoscopic slant. Liu, Berends, and Schor (2005) and Berends et al. (2006) demonstrated the existence of mechanisms that compare these signals to one another and recalibrate them. The felt eye position is affected by proprioception, efference copy, and retinal disparity.

The retinal information might be suppressed by the eye position signal, which is from efference copy and oculomotor proprioception,

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[1] Both the groups of Banks and Erkelens have done interesting work on this regarding perceived visual direction near an occluder that was defined by disparity. They showed that under some conditions the position of an object on the retina relative to the center of the retina does not specify the observer's perceived direction (van Ee, Banks & Bakus, 1999; Erkelens & van Ee, 1997).

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as there is cue conflict between the eye position-specified direction and the disparity-specified direction in displays used in those reports. In a parallel cue system, information from one cue may conflict with that from another. Such conflicts can be resolved in several ways (Howard & Rogers, 2002): cue averaging and summation, cue dominance, cue dissociation, cue reinterpretation, and cue disambiguation. The information from the eye position signal (i.e., oculomotor proprioception and efference copy) and that from the disparity are probably combined in the way of cue dominance; disambiguation is not an option for these stimuli because no physical stimulus produces such a conflict. In other words, direction judgments were based only on the eye position signal, with the disparity information being suppressed.

The manner in which cues are combined can be altered by a change in the reliability of the cue. A way to combine suprathreshold signals from different cue systems is to take the weighted mean, with weights determined by some estimate of the reliability of each cue. The weighted signals are summed and then normalized. These processes can be achieved by inhibitory linkages between the coding processes (Groh, 2001). If the reliability of the eye position signal cue is lowered, the suppression of the disparity-specified signal may be weakened.

There are two ways to investigate the relative contributions of proprioception and efference copy; they might alter the reliability of the eye position signal from them. One way is the interruption of proprioceptive signals, and the other is passive ocular displacement. The former method can be achieved in two ways. One of these is to cut the proprioceptive fibers (Fiorentini & Maffei, 1977; Graves, Trotter, & Fregnac, 1987; Kashii, Matsui, Honda, Ito, Sasa & Takaori, 1989; Ludvigh, 1952; Skavenski, 1972; Trotter, Fregnac, & Buisseret, 1987) but this is not suitable for human observers. The paralytic method using eye drops is another way of invalidating the proprioception (Brindley, Goodwin, Kulikowski, & Leighton, 1976; O'Keefe & Berkley, 1991; Matin, Picoult, Stevens, Edwards, Young & MacArthur, 1982). There are also two methods to achieve ocular displacement, which dissociates eye position from ocular efference. The first involves pressing the eye with the observer's finger (Bridgeman, 1979; Bridgeman & Delgado, 1984; Bridgeman & Fishman, 1985; Bridgeman & Graziano, 1989; Bridgeman & Stark, 1991; Hershberger, 1984; Ilg, Bridgeman, & Hoffman, 1989; Stark & Bridgeman, 1983). Rotating the eye mechanically with a scleral suction contact lens is the other way (Gauthier, Nommay, & Vercher, 1990a, 1990b; Gauthier, Vercher, & Zee, 1994; Robinson, 1964; Skavenski, Haddad, & Steinman, 1972).

In this study, we present another way of altering the reliability of the eye position signal from proprioception and efference copy; the aim of this is to change the cue combination manner between the eye position signal and the binocular disparity signal for direction perception. Casual observation reveals that immediately after excessive eye rotation (a strong upward or sidelong glances for instance) the space appears unstable for a moment. If one makes an effort to rotate one's eyes beyond their movable limits for a while, the gaze position might deviate from the ocular efference because the brain continues to send signals to rotate the eyes although they are not able to rotate any further. Moreover, such sustained effort might exhaust the ocular muscles causing the proprioceptive signal to lose some accuracy.

The aim of this study is to reexamine whether the binocular disparity information alters the perceived direction. This study differs from related works (Banks et al., 2002; Berends et al., 2002) in that the observer makes an effort to rotate his eyes beyond their movable limits for a while before observing the display. Another aim of this study is to investigate if there is change in reliability of extraretinal eye position signals.

The roles of horizontal disparity and vertical disparity in the perception of direction were also investigated separately. Consider the viewing geometry of a situation for a target object (e.g., a square orthogonal to a cyclopean axis) that is on the right side of the observer. If both eyes are fixated on the center of the target object, the image in the right eye will be larger than that in the left eye because the right eye is closer. This difference in size results in vertical disparity between corresponding points in the square in the two eyes. There will be distance-induced disparity in the horizontal dimension as well because the difference in size scaling due to variable distance from the two eyes is present in all directions. In general, the horizontal disparity component produces depth perception. The vertical disparity component produces depth perception from the induced effect (Banks & Backus, 1998; Cagenello & Rogers, 1990; Gillam & Lawergren, 1983; Howard & Kaneko, 1994; Mayhew & Frisby, 1982; Ogle, 1938) and the perception of absolute distance (Rogers & Bradshaw, 1993).

2. Methods

2.1. Apparatus

The stimulus was generated by a Macintosh G4 computer and rear projected on a screen by a CRT projector (Barco Graphics 800), that displayed $1024 * 768$ pixels at a refresh rate of 120 Hz. The display size was $1024 * 768$ mm. Subjects observed the stimulus through a pair of liquid crystal shutter glasses (CrystalEyes 3) at a frame rate of 120 Hz (60 frames/s to each eye). The dichoptic half-images were selectively presented to each eye of the observer through the glasses. The viewing distance was 50 cm. Angular subtense of a pixel was $7'$ at screen center. There was no noticeable flicker at this frame rate and no visible crosstalk between the two half-images. The experimental room was carefully darkened so that, throughout the experiment, the observer saw nothing but the stimulus. The observer's head was restrained by a chin rest.

2.2. Stimuli

The experimental stimuli were sparse random-dot displays that simulated a plane on a black background. Inter-pixel positions were achieved using hyper-pixels (gamma correction for luminance was done at the screen center). Each dot was composed of $2 * 2$ pixels and subtended approximately $14'$ in the center of the display. 1000 dots were randomly distributed within a square subtending $60° * 60°$. A cross-shaped fixation target was at the center of the display. Each stimulus appeared at the screen center so that the eye position signal from proprioception and efference copy indicated the fixation target located straight ahead on observation.

The eye position-specified direction and the disparity-defined direction were independently manipulated. The same disparity patterns that usually occur when a target that is not straight ahead is fixated without head movement, were simulated and tested. The disparity-defined direction varied from $-30°$ to $30°$ in steps of $15°$ (negative values indicate leftward in this paper). The simulated distance was 50 cm. In other words, although the stimuli always appeared to be straight ahead physically, some of them contained direction information from disparity patterns that indicate eccentricity. The actual VSR values for $-30°$, $-15°$, $15°$, and $30°$ were 0.937, 0.967, 1.034, and 1.067, respectively.

In addition, the roles of horizontal and vertical disparities on perception of direction were investigated by separating the disparity pattern into horizontal and vertical disparity components. Three different disparity patterns were then tested; displays with a horizontal disparity component only, displays with a vertical disparity component only, and displays with both horizontal and vertical disparity components.

2.3. Procedure

The outline of each trial is as follows. First, the observer was asked to rotate his eyes excessively. Next, a test display was presented. Then the observer indicated the perceived direction with an unseen pointer. On each trial, a cross-shaped fixation target appeared at the center of the screen and the observer was asked to fixate it. After 10–15 s, the fixation target switched off and a tone informed the observer to attempt to rotate his eyes beyond their movable limit. After 15 s eye rotation, another tone informed the observer to quit the excessive eye rotation and to turn his eyes to the subject straight ahead. A test stimulus appeared on the screen just after the tone. The observer was asked to fixate a cross-shaped fixation target at the center of the stimulus and to judge its direction. The display was presented for 3 s and then it disappeared. The observer indicated the perceived direction with an unseen pointer. (The observer was allowed to start adjusting the pointer during the stimulus exposure.)

The disparity-defined direction varied from $-30°$ to $30°$ in steps of $15°$. Three types of disparity information were displayed: the horizontal disparity component alone (VSR = 1), vertical disparity component alone (HSR = 1), both the horizontal and vertical disparity components (HSR = VSR). The direction of the excessive eye rotation was to the upper right or upper left. The disparity direction, type of disparity information, and direction of eye rotation were varied randomly from trial to trial. Each combination was tested 10 times. The experimenter gave a verbal instruction as to the direction of the excessive eye rotation before each trial. All of the experimental conditions described in this paragraph were tested randomly in a blocked experiment.

A second experiment to investigate the effect of the excessive eye rotation was conducted as a separate block. The procedure for this experiment was similar to that of the experiment described above, but without the excessive eye rotation stage. The disparity direction and type of disparity information were varied randomly from trial to trial. Each combination was tested 10 times.

2.4. Response measures

A stick pointer, 18 cm long, was placed in front of the observer at chest height. The pointer could be pivoted about a point near the chest. The observer was asked to adjust the pointer, without being able to see either the pointer or his hands, until he felt that it pointed in the same direction as the visually perceived direction. After adjusting, he pressed a button, and the direction was recorded. The direction was determined with a one-turn potentiometer and the output acquired via an AD converter. The precision of the device was better than 1°.

In a control condition, the screen was replaced by a real board that was covered with a grid pattern. Eleven marks formed a line on the board at eye height. They were eccentrically located at ±0°, 3°, 6°, 9°, 12°, 15°, 18°, or 21°, giving 15 values in total. The observer moved the pointer to match the position of each mark that was selected randomly. The marks had a full range of binocular and monocular depth cues because this experiment was carried out in a well-illuminated environment. A board was placed between the observer's eyes and his hands so that he could see neither the pointer nor his hands. The observer made four settings for each direction. The functions relating the pointer response to the real mark direction were monotonic, but non-linear. A third-order polynomial function was used to fit the calibration data for each subject.

2.5. Observers

Four observers (aged between 22 and 39 years), who were screened from 10 observers, participated in this experiment. They all had normal or corrected to normal visual acuity and also normal stereo acuity confirmed by Lang stereotest #1 and #2. All could perceive slant from the induced effect. Except for MI, all observers were naïve with regard to the experimental hypotheses.

3. Results and discussion

The results are plotted in Fig. 1. Each set of three panels in a row represents the data from a different observer. In Fig. 1, the mean perceived direction is plotted as a function of the disparity-defined direction. Each error bar shows the standard error. Different symbols represent the different disparity information presented. The panels in each column represent the data from a different pre-observation condition. The panels in the left column represent the data from the experiments without the excessive eye rotation prior to observation. The panels in the middle column represent the data from the experiments with excessive eye rotation (to the upper right) prior to observation. The panels in the right column represent the data from the experiments with excessive eye rotation (to the upper left). As in Banks et al. (2002) and Berends et al. (2002), without the excessive eye rotation prior to observation, there is no evidence of the use of disparity information in direction perception. Even without the eye rotation, one observer (SK) showed a small effect when the disparity pattern with both horizontal and vertical disparity components was displayed. With the excessive eye rotation, the effect of the disparity pattern on the perceived direction was consistent for all observers when the disparity pattern consisted of both horizontal and vertical disparity components. Even with excessive eye rotation, vertical disparity alone did not alter the perceived direction. The data under different experimental conditions were analyzed with the one-way analysis of variance (ANOVA). The factor in this analysis was the disparity-defined direction. The cut-off value is 5.56 for the F-distribution at 4° and 45° of freedom and 99.9% confidence: $F(4,45) = 5.56$, $p = 0.001$. The obtained F-values are presented in Table 1.

For verification, linear relations (least square) were fitted between the disparity-defined direction and the perceived direction to determine the gradient of the line. The gradient shows the gain of disparity information to produce the perceived direction. Fig. 2 shows the results. Each panel represents the data from a different observer. With the excessive eye rotation, the effect of the disparity pattern on the perceived direction was consistent for all observers when the disparity pattern consisted of both horizontal and vertical disparity components. One subject (SK) showed a maximum gain of 0.3. This means that when the disparity information indicated 30°, the perceived direction was 9° even though the display was physically straight ahead. The maximum gain for subject MI was 0.14. Subjects YF and SK showed a small maximum gain of 0.08.

Besides the excessive eye rotation, there is another difference between this study and other studies (especially Banks et al. (2002) which used the same method of the unseen pointer). These stimuli were larger, which would make the disparity signals more reliable. That cannot explain the result because a control experiment in which there was no excessive eye rotation, but it might have been necessary to use large stimuli, was done.

The result suggests that horizontal size ratio contributes to an estimate of head-centric direction. Real objects in eccentric locations do, on average, have a horizontal size that is larger in the closer eye as well as having a vertical size that is larger in the closer eye. Thus, it is plausible that HSR could have some ecological validity for specifying azimuth, especially in combination with an equal magnitude VSR.

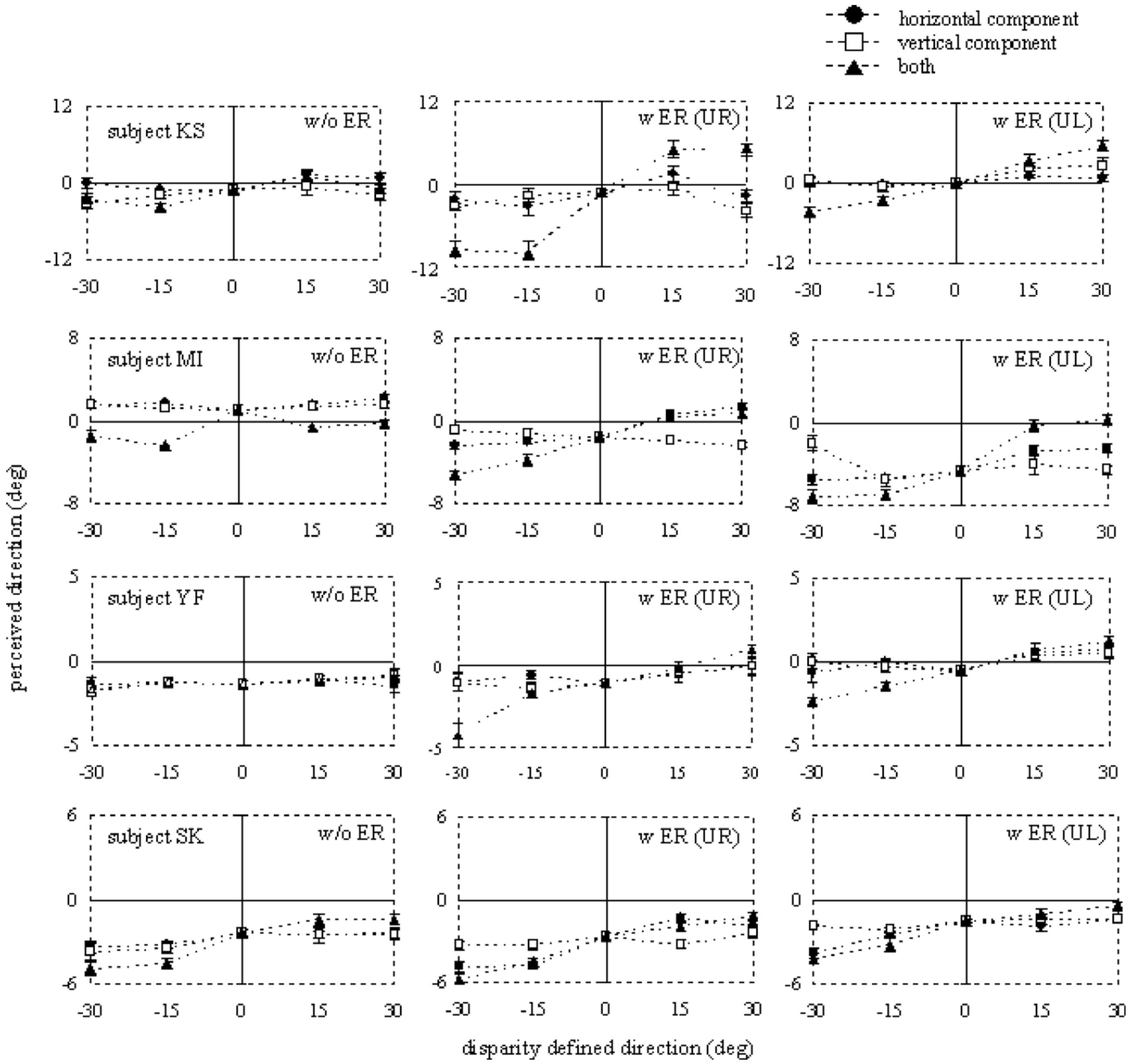

Fig. 1. The perceived direction plotted as a function of the disparity-defined direction. Note the difference in the *y*-axis coordinates for the four observers. ER, UR, and UL stand for eye ration, upper right, and upper left, respectively.

Table 1
The obtained *F*-values by one-way ANOVA.

	Without eye rotation			With eye rotation (UR)			With eye rotation (UL)		
	H	*V*	Both	*H*	*V*	Both	*H*	*V*	Both
KS	2.78	1.94	4.1	3.46	3.77	66.15	1.36	4.18	32.46
MI	0.78	0.25	8.29	35.07	2.6	51.49	8.41	3.9	35.69
YF	0.18	1.02	1.33	1.29	2.21	20.77	2.13	1.73	20.11
SK	2.26	2.05	19.27	20.24	1.51	30.49	9.54	2.43	19.79

$F(4,45) = 5.56$, $p = .0001$.

4. A supplementary experiment

A supplementary experiment was conducted to investigate if the observers have fusion after the huge and unusual eye rotation. This can demonstrate whether disparity processing still takes place after the eye's huge rotation. In this experiment, a figural 3D aspect was added to the set of sparse dots which facilitates a detection task. There was a central area subtending $5° * 5°$ that was either in front or behind the other dots. The other conditions were similar to the main experiment. The observer's task here was to detect the

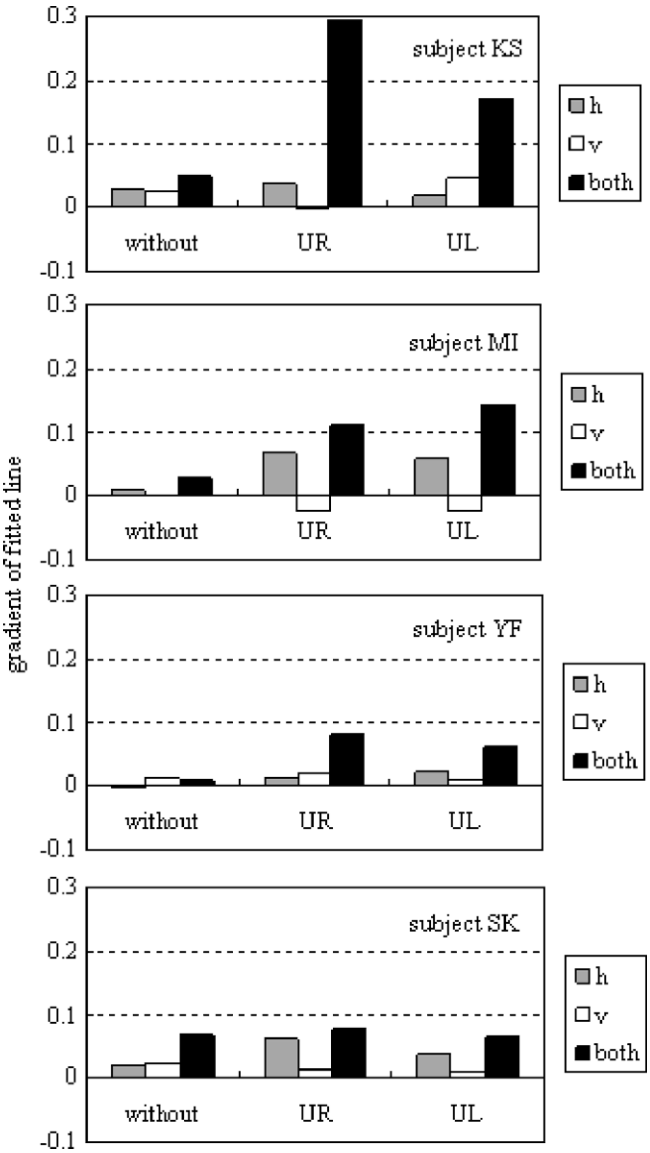

Fig. 2. The gradient of the linear functions fitted between the perceived direction and the disparity-defined direction. UR and UL stand for upper right and upper left eye rotation, respectively.

relative depth after 15 s eye rotation. The disparity value given to the central area was 6.6′ for uncrossed and 7.2′ for crossed disparity. All observers perceived the correct relative depth. The results showed that the correct fusion has taken place and disparity processing still takes place after the eye's huge rotation.

5. Conclusions

The findings of this study are summarized below. Binocular disparity information alters the perceived direction when both horizontal and vertical disparity components are displayed simultaneously. This is true only when the observer makes an effort to rotate his eyes beyond their movable limits for a short while before observing the display. This suggests that the retinal information is suppressed by the eye position signal from efference copy and oculomotor proprioception in normal observations. Moreover, the excessive eye rotation prior to observation alters the reliability of the eye position signal from proprioception and efference copy and the manner in which cues from eye position and binocular disparity signals are combined for direction perception, is altered.

The gain from using disparity information to identify the perceived direction was small in this research. The excessive eye rotation certainly altered the combination manner. The weight given to the eye position signal, however, was still much higher than that of the disparity information for estimating direction.

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