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Letters to the Editor

The Computation of Binocular Visual Direction: A Re-examination of Mansfield and Legge (1996)

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Mansfield and Legge (1996) reported recently that a target's perceived binocular direction is dependent on the ratio of contrasts presented to the two eyes. Although their main conclusion concerned the dependence of perceived direction on interocular contrast, they also argued that the change in perceived direction is due to a shift in the position of the cyclopean eye and that the relative directions of binocular targets are unaffected by eye position. We take issue with both of these arguments. With regard to the former, their task was an alignment task, not an egocenter task, so it did not provide information relevant to the position of the cyclopean eye. Indeed, their data can be explained by the conventional theory of binocular visual directions with a fixed cyclopean eye (e.g., Hering, 1879; Ono, 1981) once a simple, but important modification is added. With regard to their conclusion concerning eye position, we show that the vergence of the eyes has a clear and systematic effect on perceived relative directions in the setup used by Mansfield and Legge. © 1997 Elsevier Science Ltd.

Cyclopean Binocular Stereopsis Vergence Direction

The estimation of visual direction for a binocular target is ambiguous when the target's images fall on different locations in the two eyes. Consider a situation in which the eyes are in primary gaze and the image locations are similar enough for the images to be fused. The perceived oculocentric visual direction of the fused image could be that of the image from the left or right eye alone (e.g., Walls, 1951) or it could be the average of the oculocentric directions of the two monocular images. There is much empirical support for the averaging of the monocular images, so the conventional theory of perceived visual direction, articulated originally by Wells and Hering and augmented by Ono and others (e.g., Hering, 1879; Ono, 1981; Wells, 1792), states that the oculocentric direction is the average of the monocular images. The conventional theory also states that the derived visual direction will be perceived as if the observer were viewing the scene from a single point between the eyes; this point is the cyclopean eye.

Figure 1 depicts the geometry of the conventional theory of binocular visual direction. The observer is fixating a point in the head's median plane, so the eyes are in primary gaze. The visual axes are represented by thick lines. A binocular target is also shown along with its corresponding visual lines. The angles between the visual axes and lines are α_L and α_R for the left and right eyes, respectively; these correspond to the oculocentric directions of the target in each eye. The binocular visual direction corresponds with the angle between the median plane and a line from the midpoint of the interocular axis to the target. That angle α_B can be estimated by the following equation:

$$\alpha_B = (\alpha_R + \alpha_L)/2 \qquad (1)$$

According to the conventional theory, the target has a perceived direction of α_B and is seen as if it were viewed from the cyclopean position midway between the eyes.§ We will refer to the line from the cyclopean eye through the apparent position of the target as a *binocular direction line*.

Great care is needed to avoid confusion among tasks involving the determination of binocular visual direction. Howard and Templeton (1966) draw a clear distinction between *alignment tasks* and *egocenter tasks* (they refer to the latter as *judged egocenter tasks*). In alignment tasks, the observer is asked simply to position near and far targets until they appear in the same visual direction (e.g., Erkelens & van de Grind, 1994; Sheedy & Fry, 1979). These tasks do not provide information about the location of the cyclopean eye. In particular, the observation of a change in perceived alignment does not tell us whether the binocular direction line to one of the targets

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§There has been much discussion as to whether the cyclopean eye is on the interocular axis or on the Vieth–Müller Circle. We ignore this issue here.

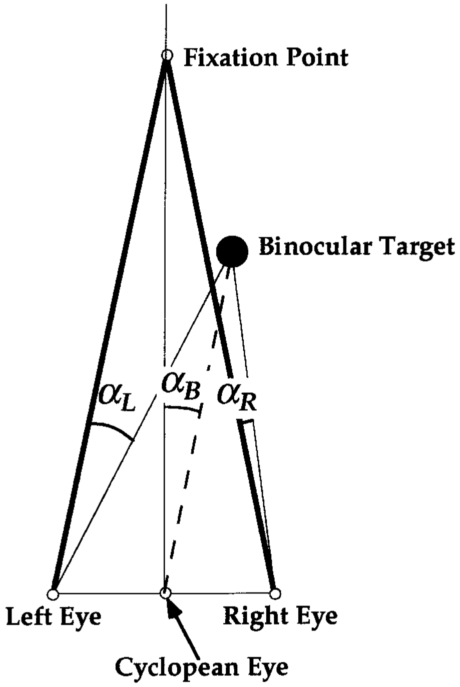

FIGURE 1. Geometry involved in estimating binocular visual direction. Fixation is on a point in the median plane of the head, so the eyes are in primary gaze position; the visual axes are represented by thick lines. A target is shown along with its corresponding visual lines (thin lines). α_L and α_R are the angles between the visual axes and lines for the left and right eyes, respectively. α_B is the binocular visual direction of the target (estimated from the conventional theory) and is equal to the angle between the head's median plane and a line from the midpoint of the interocular axis to the target. The dashed line from the cyclopean eye through the apparent position of the target is the binocular direction line.

rotated about a fixed cyclopean eye or whether the position of the cyclopean eye changed. In egocenter tasks, the observer is asked to indicate the part of the body with which targets appeared to be aligned (e.g., Howard & Templeton, 1966; Mitson, Ono & Barbeito, 1976; Roelofs, 1959). These tasks allow an estimation of the location of the cyclopean eye. Specifically, with such a task one can distinguish whether a change in perceived direction is due to rotation of the binocular direction line or to a change in cyclopean eye position.

It has been known for some time that interocular differences in target luminance affect perceived visual direction (Charnwood, 1949; Francis & Harwood, 1951; Verhoeff, 1933, 1935). Recently, Mansfield and Legge (1996) showed that interocular contrast differences also affect perceived direction; the main point of their paper was that one could model such effects by weighting inputs from the two eyes differently depending on the interocular contrast ratio. However, Mansfield and Legge also argued that the concept of a cyclopean eye of fixed position is incorrect; they said instead that the cyclopean eye can shift to any position on the interocular axis depending on the ratios of contrasts presented to the eyes. This point was emphasized by Mansfield and Legge (1995). We will argue here that the concept of a moving cyclopean eye is not required to explain their data. An alignment task rather than an egocenter task was used, so the data do not bear directly on the position of the cyclopean eye. Indeed, as we will show, the conventional theory can explain these data without assuming a shifting cyclopean eye; the conventional theory needs a simple, but important modification, also made by Mansfield and Legge, that allows different weights to be given to the monocular direction measurements.

Mansfield and Legge (1995, 1996) also argued that eye position does not affect relative visual direction. We will show that eye position (specifically vergence) has a clear and systematic effect on perceived direction; the effect is consistent with the conventional theory. For reasons given below, we assume that the vergence of Mansfield and Legge's observers varied with viewing condition in their experiment.

Figure 4(B) demonstrates the phenomenon that led to Mansfield and Legge's conclusion that the cyclopean eye shifts with changes in the viewing situation. A target is presented stereoscopically with a disparity different from the fixation point. The images of the target are positioned such that their average horizontal positions are the same as the fixation aid below the target. The target has greater contrast in the image presented to the right eye, and the fixation aid has the same contrast in both eyes. Because the average horizontal positions of the target and aid are the same, the conventional theory predicts that the target

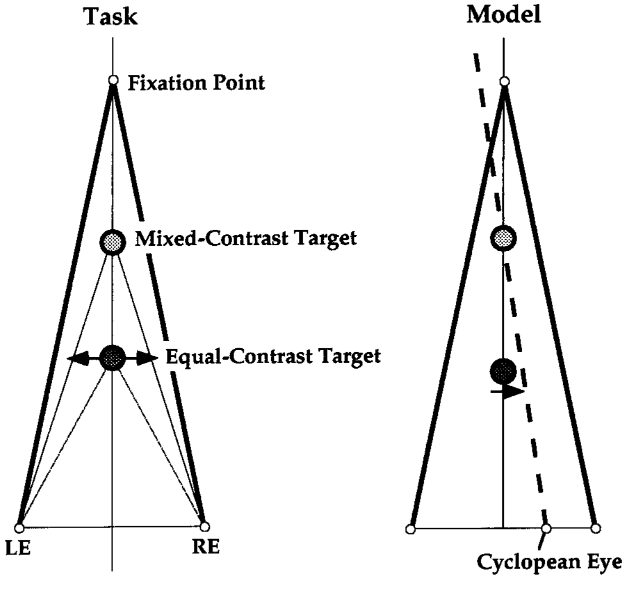

FIGURE 2. Task and model of Mansfield and Legge (1995; 1996). (A) Depiction of the task. A fixation point is presented in the plane of the background; the visual axes are represented by the thick lines. Mixed- and equal-contrast targets are presented with different disparities with respect to the fixation point. The observer adjusts the azimuth of the equal-contrast target until it appears to be aligned with the mixed-contrast target. (B) Depiction of the model. In this schematic, the contrast of the mixed-contrast target is greater in the right eye, so the cyclopean eye shifts to the right. Consequently, the equal-contrast target appears farther left than the mixed-contrast target, so the observer has to move the equal-contrast target to the right in order to achieve alignment. The cyclopean eye's position is estimated by drawing a line (represented by the dashed line) through the physical locations of the mixed- and equal-contrast targets when they appear to be aligned.

and fixation aid should appear vertically aligned. However, the mixed-contrast target appears to the left of the fixation target which shows that perceived visual direction is affected by the ratio of contrasts presented to the eyes. As Mansfield and Legge note, this shift in perceived direction is not explained by the conventional theory of visual direction.

A schematic of the Mansfield and Legge experiment is presented in Fig. 2. Two Gabor patches were presented binocularly. One patch had different contrasts in the two eyes and was always presented with a crossed disparity of 30 min arc with respect to the fixation aid. The other patch had the same contrast in the two eyes and was presented at disparities ranging from 0 to 60 min arc. Observers adjusted the horizontal position of the equal-contrast target until it appeared to be aligned with the mixed-contrast target. Mansfield and Legge reported that the displacement required to align the targets was a monotonic function of the contrast ratio in the mixed-contrast target and of the disparity of the equal-contrast target. When the contrast of the mixed-contrast target was greater in the right eye and the equal-contrast target had greater crossed disparity (and was, therefore, seen as nearer than the mixed-contrast target), observers needed to move the equal-contrast target to the right in order to achieve alignment.[*] Mansfield and Legge argued that the shift required to align the targets reveals a displacement of the cyclopean eye. A schematic of their model is presented in Fig. 2. They estimated the position of the shifted cyclopean eye by fitting a line (represented by the dashed line) to the physical locations of the mixed- and equal-contrast targets when they appear to be aligned. The intersection of the line and the interocular axis yielded the presumed position of the cyclopean eye.

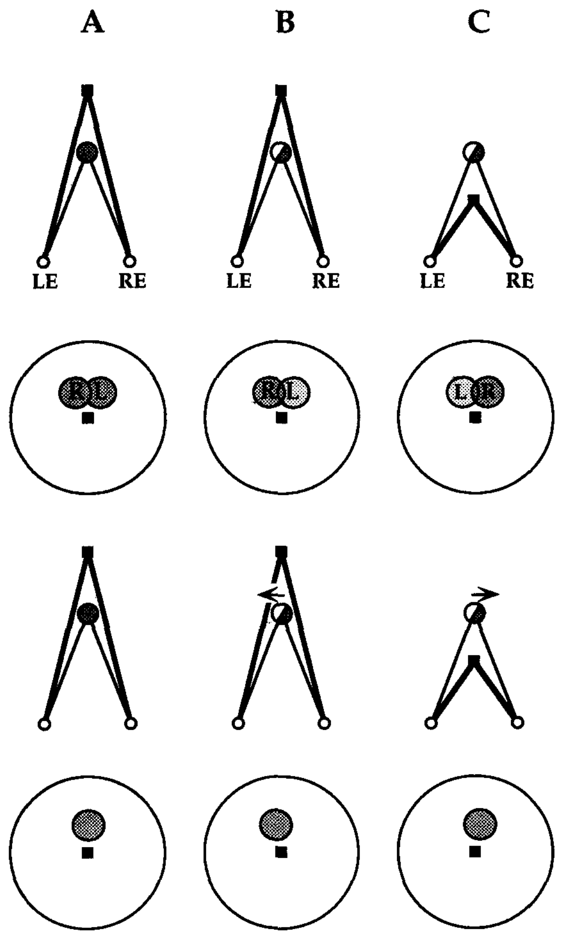

FIGURE 3. Modified conventional theory of binocular visual direction. (A) Equal-contrast target nearer than fixation. (B) Mixed-contrast target (greater contrast in right eye) nearer than fixation. (C) Mixed-contrast target farther than fixation. The perceived oculocentric direction of the target is determined by a weighted average of oculocentric directions in each eye. Notice that the displacement of the mixed-contrast target is away from the eye with greater contrast when it is nearer than fixation and toward that eye when it is farther than fixation.

The Mansfield and Legge data can be explained without assuming that the cyclopean eye shifts. To do so, we first assume that the binocular direction of a target is determined by a weighted average of the oculocentric directions measured in the eyes.[†] Specifically,

$$\alpha_B = W\alpha_R + (1 - W)\alpha_L \tag{2}$$

where α_L, α_R, and α_B are defined as before and W, which ranges from 0 to 1, is the weight given to the oculocentric direction of the target measured by the right eye. We assume that $W > 0.5$ whenever the contrast is greater in the right eye and that $W < 0.5$ whenever the contrast is greater in the left eye. When $W = 0.5$, the binocular direction is the average of the oculocentric directions measured in the two eyes; this corresponds to the conventional theory of binocular visual direction. Mansfield and Legge (1996) made an equivalent assumption about weighting the two eyes' signals [see their Eq. (5) and Appendix B].[‡]

Figure 3 illustrates how the modified conventional theory proposed here works. The upper row of the figure schematizes three viewing situations with either an equal-

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[*] When the mixed-contrast target had greater contrast in the right eye and the equal-contrast target had less crossed disparity than the mixed-contrast target, observers moved the equal-contrast target to the left to achieve alignment.

[†] For simplicity, we consider symmetric eye convergence only, so the version is 0 deg. It is, however, straightforward to include different versions and make predictions for binocular visual direction in asymmetric convergence.

[‡] Equation (5) of Mansfield and Legge (1996) appears similar to our Eq. (2). In their equation, the "left and right visual directions" are labeled L and R and the binocular visual direction is B. Figure 2 and the associated discussion in Appendix A imply that those quantities are the same as α_L, α_R, and α_B in our Eq. (2). However, this interpretation is inconsistent with their statement on p. 30 that "eye position ought not to influence the judgment of relative direction". On the other hand, their Fig. 6 and the associated discussion imply that L and R refer to the angles between the visual line to the target and a line parallel to the head's median plane that goes through the left or right eye. The latter interpretation is consistent with their statement about eye position on page 30. Finally, with either of these interpretations, their model cannot predict some of their data. Figure 4 of Mansfield and Legge shows that the equal-contrast target is *not* displaced relative to the mixed target when they have the same disparity. According to Eq. (5), however, whenever a target has mixed contrast and L and/or R are non-zero, the target should appear displaced.

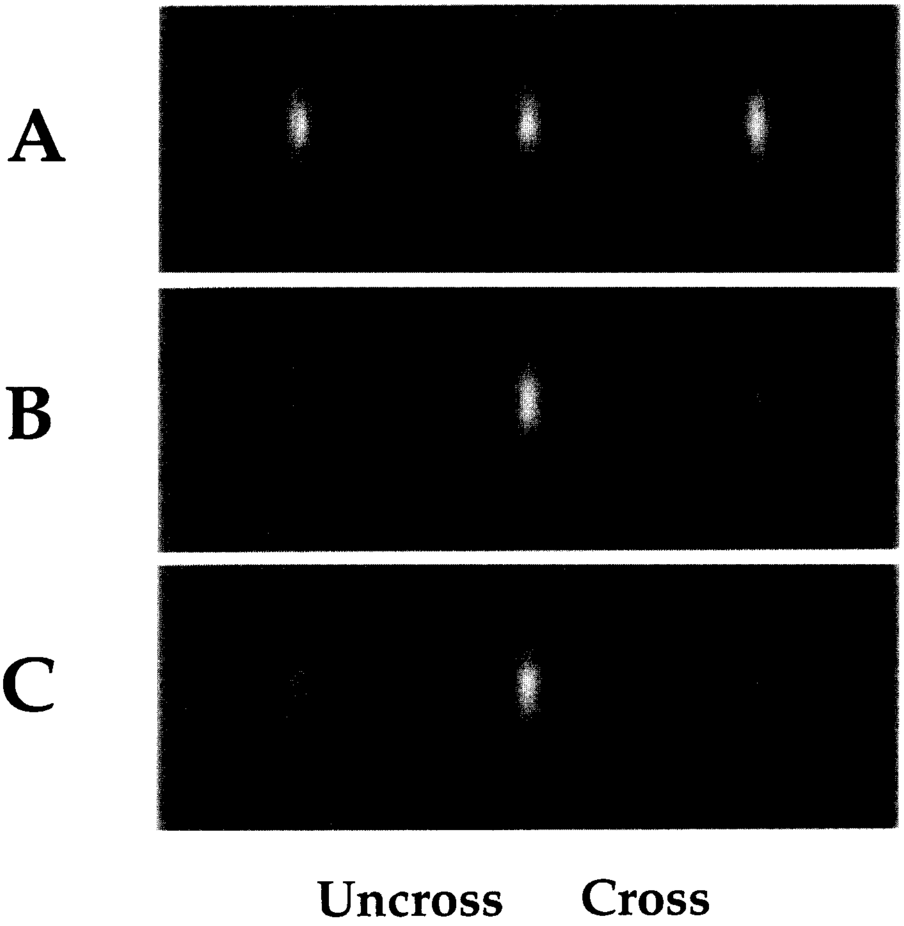

FIGURE 4. Demonstrations of binocular visual direction with equal- and mixed-contrast targets. In each panel, fixate the small fixation aid below the target; use the nonius lines to align your eyes precisely. If you fuse by diverging the eyes, use the left and middle columns. If you fuse by converging your eyes, use the middle and right columns. (A) Equal-contrast target nearer than fixation. The perceived binocular directions of the target and fixation aid are the same. (B) Mixed-contrast target (greater contrast in right eye) nearer than fixation. The perceived direction of the target is to the left of the perceived direction of the fixation aid. (C) Mixed-contrast target farther than fixation. The perceived direction of the target is to the right of the perceived direction of the fixation aid.

or mixed-contrast target (represented by the circles) and with the observer fixating either behind or in front of the target. The second row represents the monocular images of the point of fixation and the target; the monocular images have been superimposed such that the foveas are in the same position. The third row shows the predictions of the modified conventional theory; α_B is changed according to Eq. (2). The bottom row represents the predicted binocular visual direction of the target for the three viewing situations.

In situations A and B, the observer is fixating behind the target and α_L and α_R are equal in magnitude but opposite in sign (α_L is clockwise or negative). In situation A, the target is presented with equal contrast to the two eyes, so W in Eq. (2) is 0.5; $\tan\alpha_B$ is therefore equal to 0 because it is simply the average of $\tan\alpha_L$ and $\tan\alpha_R$. The target should be seen in the head's median plane. In situation B, the target has greater contrast in the right eye, so $W > 0.5$; α_B is consequently biased toward the value of α_R. The target should appear farther to the left than in situation A. The modified conventional theory characterizes the perceived shift by rotating the binocular direction line through the angle α_B, but *the position of the cyclopean eye does not change.*

In situation C, the observer is fixating in front of the target, so α_L and α_R are again equal in magnitude and opposite in sign, but their signs are reversed with respect to situation A. Because the target has greater contrast in the right eye, α_B is biased toward the value of α_R, which is positive (counter-clockwise), so the target should appear farther to the right than in situation A. Again the modified conventional theory characterizes the perceived shift by rotating the binocular direction line through the angle α_B; the position of the cyclopean eye does not change.

The shifts in perceived visual direction are demonstrated in Fig. 4. The three panels correspond to the three viewing situations schematized in Fig. 3. Fuse the targets (divergent fusers should use the left and middle columns and cross-fusers the middle and right columns) and use the nonius lines above and below the fixation aid to align your eyes accurately. In Fig. 4(A), the target appears in the same horizontal direction as the fixation aid; $\alpha_B = 0$.

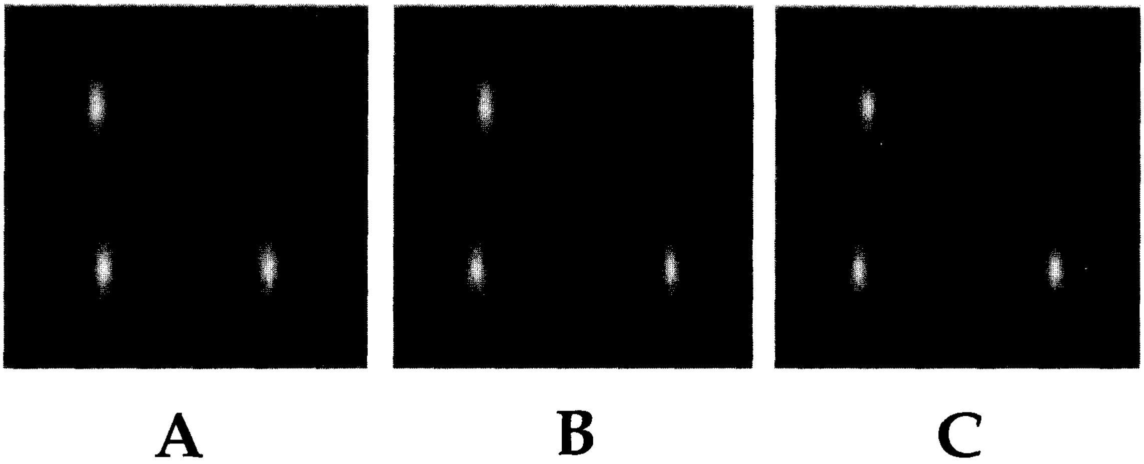

FIGURE 5. Demonstrations of the effect of varying the contrast ratio and vergence with Mansfield and Legge's (1996) stimuli. You must cross-fuse while viewing each panel. The three panels contain mixed- and equal-contrast Gabor patches and fixation aids. In (A), the mixed-contrast target has greater disparity than the equal-contrast target, so it is seen as nearer. The fixation aid has the same disparity as the equal-contrast target; the nonius lines help you assess vergence accuracy. In (B), the disparity of the mixed-contrast target is the same as in (A), but the equal-contrast target now has greater crossed disparity, so it is now seen as nearer. The fixation aid is presented in the positions used in Mansfield and Legge (1996). In (C), the disparity of the mixed-contrast target is the same as in (A) and (B), and the disparity of the equal-contrast target is the same as in (B). The fixation aid is presented where we believe Mansfield and Legge's observers were actually verged.

In Fig. 4(B), the target appears to the left of the fixation aid; $\alpha_B > 0$. In Fig. 4(C), the target appears to the right of the aid; $\alpha_B < 0$.

The displays in Fig. 4 demonstrate that variations in the contrast ratio between the left and right eye images affect the perceived direction of a binocular target and, as you can see by referring to Fig. 3, one does not need to assume a change in the position of the cyclopean eye in order to explain the change in apparent direction. The displays in Fig. 4 also demonstrate that the observer's vergence affects the perceived direction of a target. With the added feature of varying weights attached to the monocular measurements of direction, these observations are completely consistent with the conventional theory of binocular visual direction.

Can this theory explain Mansfield and Legge's (1996) data? Fig. 5, which is similar to their Fig. 3, shows that it can. The left, middle, and right panels contain mixed- and equal-contrast Gabor patches and fixation aids. You must cross-fuse while viewing these stimuli. In Fig. 5(A), the mixed-contrast target has greater crossed disparity than the equal-contrast target. The fixation aid has the same disparity as the equal-contrast target; use the nonius lines to assess the accuracy of your vergence. The equal-contrast Gabor appears to the right of the mixed-contrast patch, so you would have to move it to the left to achieve alignment. This is consistent with the data in Fig. 4 of Mansfield and Legge and with the predictions of the modified conventional theory. In Fig. 5(B) and Fig. 5(C), the disparity of the mixed-contrast target is the same as in Fig. 5(A), but the equal-contrast target now has greater crossed disparity. The fixation aid in Fig. 5(B) is presented in the positions of the aids in the Mansfield and Legge (1996) experiment and the aid in Fig. 5(C) in the positions that correspond to where we believe the observers were actually verged. Use the nonius lines to assess the accuracy of your fixation. If you fixate the crosses in Fig. 5(B) (as Mansfield and Legge's observers were instructed), the equal-contrast patch appears to the right of the mixed-contrast patch, which is *inconsistent* with the data in their Fig. 4. However, when you fixate the aid in Fig. 5(C), the equal-contrast patch appears to the left of the mixed one and this is *consistent* with Mansfield and Legge's data. We hypothesize, therefore, that their observers did not follow the fixation instructions; if they had, they would not have obtained the data of Fig. 4. Specifically, we hypothesize that their observers' fixation was biased toward the plane of the equal-contrast target. Mansfield and Legge did not monitor eye position because of their belief that eye position ought not influence judgments in their experiments, so there is no way to determine the actual vergence state of their observers across conditions.

In summary, Mansfield and Legge's conclusion that the position of the cyclopean eye is dependent on the ratio of contrasts presented to the two eyes is inappropriate for two reasons. First, they used an alignment task which does not provide information about the position of the cyclopean eye *per se;* indeed, we showed that the conventional theory of binocular visual direction (with a simple, but important modification that could be implemented in the fashion suggested by Mansfield and Legge) can predict their data without assuming a change in the cyclopean eye's position. The modified conventional theory can also account for changes in perceived direction when target luminance is reduced in one eye (Charnwood, 1949; Francis & Harwood, 1951; Verhoeff, 1933, 1935) and when a target is seen by one eye because of an occluding edge (Erkelens & van de Grind, 1994; Erkelens, Muijs & van Ee, 1996). Second, despite

Mansfield and Legge's assertion that vergence state does not affect perceived alignment, we have shown that the perceived relative directions of mixed- and equal-contrast targets are in fact affected by eye position as predicted by the conventional theory of binocular visual direction.

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Binocular Visual Direction, the Cyclopean Eye, and Vergence: Reply to Banks, van Ee and Backus (1997)

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INTRODUCTION

Banks *et al.* (1997) discuss two issues arising from our investigations of the influence of interocular contrast differences on binocular visual direction (Mansfield & Legge, 1995, 1996). The two issues are (1) whether or not the cyclopean eye is displaced towards the eye with higher contrast; and (2) the role of vergence in the computation of visual direction. In general, we accept Banks and colleagues' two points, but their comments do not challenge the principal conclusion from our study.

In our original study (Mansfield & Legge, 1996) we measured the horizontal location at which a binocularly viewed Gabor target with equal contrast in each eye appeared aligned with another target at a different depth, and with different contrasts in each eye. We found that the alignment point was not determined by the simple average of the left and right eye's direction signals as predicted by the prevailing theories of binocular visual direction (see Ono, 1991; Ono & Mapp, 1995). Instead, our data showed that the perceived alignment between the mixed- and equal-contrast Gabors was determined by a weighted average of the direction signals from the left and right eyes. We proposed a model for the weighting of

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