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.

REFERENCES

Charnwood, J. R. B. (1949). Observations on ocular dominance. *The Optician, 116*, 85–88.

Erkelens, C. J., Muijs, A. J. M. & van Ee, R. (1996). Binocular alignment in different depth planes. *Vision Research, 36*, 2141–2147.

Erkelens, C. J. & van de Grind, W. A. (1994). Binocular visual direction. *Vision Research, 34*, 2963–2969.

Francis, J. L. & Harwood, K. A. (1951). The variation of the projection center with differential stimulus and its relation to ocular dominance. In *Transactions of the International Congress* (pp. 75–87). London: British Optical Association.

Hering, E. (1879). *Spatial sense and movements of the eye*. (English translation by Radde, C. A.). American Academy of Optometry, Baltimore, 1942.

Howard, I. P. & Templeton, W. B. (1966). *Human spatial orientation*. London: Wiley.

Mansfield, J. S. & Legge, G. E. (1995). Is there more than one cyclopean eye for visual direction? *Investigative Ophthalmology and Visual Science, 36*, S813.

Mansfield, J. S. & Legge, G. E. (1996). The binocular computation of visual direction. *Vision Research, 36*, 27–41.

Mitson, L., Ono, H. & Barbeito, R. (1976). Three methods of measuring the location of the egocentre: their reliability, comparative locations and intercorrelations. *Canadian Journal of Psychology, 30*, 1–8.

Ono, H. (1981). On Well's (1792) law of visual direction. *Perception and Psychophysics, 30*, 403–406.

Roelofs, C. O. (1959). Considerations on the visual egocentre. *Acta Psychologica, 16*, 226–234.

Sheedy, J. E. & Fry, G. A. (1979). The perceived direction of the binocular image. *Vision Research, 19*, 201–211.

Verhoeff, F. H. (1933). Effect on stereopsis produced by disparate retinal images of different luminosities. *Archives of Ophthalmology, 13*, 151–175.

Verhoeff, F. H. (1935). A new theory of binocular vision. *Archives of Ophthalmology, 13*, 151–175.

Walls, G. L. (1951). A theory of ocular dominance. *Archives of Ophthalmology, 45*, 387–412.

Wells, W. C. (1792). *An essay upon single vision with two eyes; together with experiments and observations on several other subjects in optics*. London: T. Cadell.

Acknowledgements—We thank Clifton Schor and James Crowell for helpful discussions. This research was supported by AFOSR Research Grant 93NL366, NSF Research Grant DBS-9309820, and NIH Training Grant EY-07043.

Pergamon

Vision Res., Vol. 37, No. 12, pp. 1610–1613, 1997
© 1997 Elsevier Science Ltd. All rights reserved
Printed in Great Britain
0042-6989/97 $17.00 + 0.00

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

J. STEPHEN MANSFIELD,*† GORDON E. LEGGE*

Received 25 October 1996

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

---

*Department of Psychology, University of Minnesota, 75 East River Road, Minneapolis, MN 55455, U.S.A.

†To whom all correspondence should be addressed.

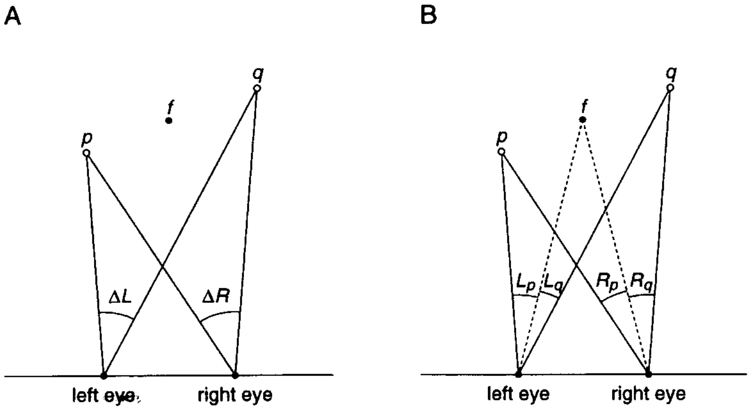

FIGURE 1. Models for the binocular computation of visual direction. (A) The scheme described by Mansfield & Legge (1996), see text for details. (B) The scheme proposed by Banks *et al.* (1997), see text for details.

the monocular inputs in the computation of binocular visual direction. In our model, the left and right eye's inputs are weighted according to the spatial uncertainty associated with their alignment signals. We obtained empirical support for this model in a second experiment in which we showed that the magnitude of the contrast-induced change in visual alignment was predicted by the ratio of the vernier acuities for performing the alignment task monocularly in each eye. We also illustrated that this model could account for the effect of interocular contrast differences on binocular vernier acuity.

THE LOCATION OF THE CYCLOPEAN EYE

We described (Mansfield & Legge, 1996, p. 32) the change in the perceived relative direction of the mixed- and equal-contrast targets (as interocular contrast was varied) as being consistent with a corresponding change in the location of the cyclopean eye.* We agree with Banks *et al.* (1997) that, because our experimental task did not involve judgments relying on egocentric coordinates, we cannot directly claim that the location of the cyclopean eye had moved. However, Banks *et al.* imply that the movement of the cyclopean eye was a central finding of our data and subsequent analysis. It was not. Our analysis was based upon the orientation of the line that connected the mixed-contrast target to the equal-contrast targets with which it appeared aligned (angle *B* in Mansfield & Legge, 1996, Fig. 6). In other words, our analysis did not depend on whether the change in the direction of the binocular visual line was also accompanied by a change in the location of the cyclopean eye.†

For clarity it helps to make a distinction between the cyclopean eye and what we call the effective viewpoint. The cyclopean eye is the perceived location from which egocentric direction judgments are made, the location of the perceived "self". In the laws of visual direction (Ono, 1991) the visual directions from the monocular images are transferred to the cyclopean eye. The effective viewpoint is the physical location from which objects are viewed. This distinction is made clear when considering a situation in which an observer aligns two features (at different depths) that are presented only to the left eye. When the two points are aligned they will physically point to the left eye (in this case the left eye is the effective viewpoint). However, the observer will perceive the points as if they pointed straight to him, to a location midway between his left and right eyes (the cyclopean eye) (Ono, 1991).

In our experiment (Mansfield & Legge, 1996) there is no doubt that when the mixed- and equal-contrast targets appeared aligned, they pointed to a location closer to the eye seeing the higher contrast image. In our experiment the effective viewpoint moved. The perceived spatial layout of the targets was as if the scene was being viewed from a point shifted towards the eye with the higher contrast image. Similar results have been reported for interocular differences in blur (Charnwood, 1949) and interocular differences in luminance (Charnwood, 1949; Francis & Harwood, 1951).

The distinction between the cyclopean eye and the effective viewpoint has been blurred in many studies of binocular visual direction (eg Charnwood, 1949; Francis & Harwood, 1951; Erkelens & van de Grind, 1994). Most recently, Erkelens *et al.* (1996) described their binocular alignment results in terms of a *local center of direction*, which could be located at either the left eye, the right eye, or midway between the eyes, depending on whether the alignment targets were in the neighborhood of a monocularly occluded region. This is functionally equivalent to our "effective viewpoint". Their study,

---

*In Mansfield & Legge (1996) we avoided using the term *cyclopean eye* in favor of *binoculus*. We defined the binoculus to be the location from which judgments of relative direction are made. At the time, we considered the binoculus to be equivalent to the the cyclopean eye.

†At the 1995 annual meeting of the Association for Research in Vision and Ophthalmology (Mansfield & Legge, 1995) we directly addressed the issue of the location of the cyclopean eye in our mixed-contrast experiments. Banks and colleagues' comments concerning the cyclopean eye are more relevant to this presentation.

along with the others listed above, is subject to the same criticism leveled at our paper by Banks *et al.* (1997).

THE ROLE OF VERGENCE

The main difference between our model (Mansfield & Legge, 1996) and the model of Banks *et al.* (1997) is the role of the vergence state in binocular alignment judgments. In our model (Mansfield & Legge, 1996) we assumed that vergence was not an important parameter when determining the relative directions of features. Banks *et al.* (1997) argue that this assumption was invalid, and they provide a model that includes eye position in the computation of binocular visual direction. The difference between our models is related to the difference between two generic models for monocular vernier alignment. In one, the *spatial filter* model, alignment is signaled by oriented spatial filters sensitive to the offset between the vernier targets (e.g. Wilson, 1986). Such a mechanism can account for the hyperacuity performance found in vernier acuity tasks. The second model compares the *local sign* of the vernier targets. This mechanism is generally associated with poorer vernier acuity thresholds.

In our model [shown in Fig. 1(A)] the binocular alignment is determined from relative alignment cues in the monocular images that might be signaled by a *spatial filter* mechanism. The relative alignment of points p and q is determined from the relative alignment between these points in the left and right eyes' views: L and R. The binocular alignment, B, is calculated using our weighting rule based on the uncertainties associated with L and R, according to the following expression:*

$$\Delta B = w\Delta L + (1 - w)\Delta R \qquad (1)$$

where w determines the weights given to the left and right signals. L and R are constant irrespective of vergence, and thus this scheme does not depend on the vergence state of the eyes.

The scheme proposed by Banks *et al.* is illustrated in Fig. 1(B). Their model does not make use of relative alignment cues in the monocular images. Instead it relies on the *local sign* of each feature (i.e., the position with respect to fixation). The binocular visual directions of points p and q are determined separately (using a weighted average of the left and right local signs to include the effects of contrast), and then their relative alignment is determined from the difference between their binocular directions. This can be expressed as follows:

$$\Delta B = [w_p L_p + (1 - w_p)R_p] - [w_q L_q + (1 - w_q)R_q] \quad (2)$$

where w_p and w_q determine the weighting used in calculating the binocular direction of p and q respectively. The values L_p, R_p, L_q, and R_q represent the retinal coordinates of points p and q in the left and right eyes. As such, the calculation of the relative alignment of the targets depends on the position of the eyes. It is important to note that in the absence of differential weighting of the left and right eyes' signals, Eqs (1) and (2) become identical.

The demonstrations provided by Banks *et al.* (1997) are consistent with their model, clearly showing that vergence can have a marked influence on the perceived alignment of targets like those used in our original experiments. The Banks *et al.* finding suggests that binocular vernier alignment judgments are unable to take advantage of the relative alignment cues in the monocular images. This is consistent with the phenomenon of *fusional suppression* (McKee *et al.*, 1990; McKee & Harrad, 1993). When a depth difference is introduced between the components of a vernier target, binocular vernier thresholds deteriorate (as compared to monocular vernier acuity using the same stimulus configuration). McKee & Harrad (1993) explained this effect within a system where low-frequency binocular mechanisms suppress the more sensitive alignment signal from monocular mechanisms. The current findings, however, suggest that the deterioration in vernier acuity may be due to binocular judgments of alignment relying on a local-sign mechanism.

Banks *et al.* (1997) have shown circumstances in which our relative-alignment model fails to predict the perceived alignment of the mixed- and equal-contrast Gabors used in our original study. However, this does not necessarily rule out the vergence-independent relative-alignment model. Our model may explain binocular alignment for stimulus configurations in which the spatial-filter signal plays a stronger role in the alignment judgment. For example, the vernier stimuli in our original study, and in the demonstrations provided by Banks *et al.* may be too widely separated to optimally activate a spatial-filter mechanism. It remains to be seen whether reducing the vertical separation between the binocular vernier targets, a manipulation that would presumably increase the strength of the monocular alignment signals, will lead to the perceived alignment becoming less dependent on vergence state.

CONCLUSION

In stereo depth perception, there is a distinction between disparity and veridical depth perception. Disparity is determined from differences in the retinal image positions, while veridical depth requires disparity and an additional calibrating factor such as eye position or vergence. The arguments raised by Banks *et al.* (1997) suggest that there is a similar distinction to be made between visual alignment (i.e., relative direction) and egocentric visual direction (i.e., absolute direction, requiring known vergence and egocenter). Our data speak to the perception of relative direction whereas the model proposed by Banks *et al.* addresses absolute direction. In either case, the central finding of our original study still holds. When there are interocular differences in contrast, the left and right eyes' direction signals are

---

*This expression is equivalent to that presented in the Appendix of Mansfield & Legge (1996).

differentially weighted in the binocular computation of visual direction.

REFERENCES

Banks, M. S., van Ee, R. and Backus, B. T. (1997). The computation of binocular visual direction: A re-examination of Mansfield and Legge (1996). *Vision Research, 37*, 1605–1610.

Charnwood, J. R. B. (1949). Observations on ocular dominance. *The Optician, 116*, 85–88.

Erkelens, C. J., Muijs, A. J. M. & van Ee, R. (1996). Binocular alignment in different depth planes. *Vision Research, 36*, 2141–2147.

Erkelens, C. J. & van de Grind, W. A. (1994). Binocular visual direction. *Vision Research, 34*, 2963–2969.

Francis, J. L. and Harwood, K. A. (1951). The variation of the projection center with differential stimulus and its relation to ocular dominance. In *Transactions of the International Congress*, pp. 75–87. London: British Optical Association.

Mansfield, J. S. & Legge, G. E. (1995). Is there more than one cyclopean eye for visual direction? *ARVO Abstract, Investigative Ophthalmology and Visual Science, 36*, S813.

Mansfield, J. S. & Legge, G. E. (1996). The binocular computation of visual direction. *Vision Research, 36*, 27–41.

McKee, S. P. & Harrad, R. A. (1993). Fusional suppression in normal and stereoanomalous observers. *Vision Research, 33*, 1645–1658.

McKee, S. R., Levi, D. M. & Bowne, S. F. (1990). The imprecision of stereopsis. *Vision Research, 30*, 1763–1779.

Ono, H. (1991). Binocular visual directions of an object when seen as single or double. In Regan, D. (Ed.), *Vision and visual dysfunction*, Vol. 9, *Binocular vision* (pp. 1–18). London: Macmillan.

Ono, H. & Mapp, A. P. (1995). A restatement and modification of Wells–Hering's laws of visual direction. *Perception, 24*, 237–252.

Wilson, H. R. (1986). Responses of spatial mechanisms can explain hyperacuity. *Vision Research, 33*, 2685–2696.

Acknowledgement—Supported by NIH grant EY02857.