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Disparity minimisation, cyclovergence, and the validity of nonius lines as a technique for measuring torsional alignment

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Abstract. Frisby et al (1993 *Perception* **22** Supplement, 115) proposed that the visual system might make cyclovergent eye movements in order to minimise the overall pattern of both vertical and horizontal disparities when an observer views an inclined stereoscopic surface. Their measurements of cyclovergence, which used vertically oriented nonius lines, were found to be consistent with that proposal. In our experiment 1, we measured torsional eye movements objectively, using scleral coils, and found no evidence of a cyclovergent response to either a real inclined surface or to a simulated inclined surface in which the two stereoscopic images were related by a horizontal shear transformation. These results are inconsistent with the disparity minimisation hypothesis. In order to account for the discrepant findings of the two studies, we propose that vertically oriented nonius lines may not be a valid method for assessing cyclovergence because the lines can be seen as lying 'within' the inclined surface. In experiment 2, we tested the predictions of the cyclovergence hypothesis of Frisby et al against our own 'within surface' explanation, using both horizontally and vertically oriented nonius lines and dichoptic images related by either a horizontal or a vertical shear. If cyclovergence were the cause of the misalignment, both horizontal and vertical nonius lines should appear misaligned to the same extent. This was not found to be the case. We conclude that vertical nonius lines may not be a valid technique for measuring cyclovergence when the lines are seen against a background of an inclined surface.

1 Introduction

The ability of the primate visual system to make vergence as well as versional eye movements ensures that the disparities of the currently fixated object are close to zero. As a consequence, the mechanisms that detect small disparity differences can be optimised around values which are close to zero instead of being distributed over a wider disparity range. Detectors for large disparities are still needed, of course, to control vergence and allow the eyes to re-converge on an object in a different depth plane, but the resolution of the vergence control system can be coarse by comparison. As a result, vergence can be thought of as a strategy for *disparity minimisation*. The mechanisms responsible for vertical vergence have a similar consequence of aligning the eyes in a vertical direction and thereby minimising the degree of tolerance needed by the horizontal disparity mechanisms to cope with vertical misalignments. Cyclovergence—the equal and opposite torsional movements of the two eyes—can also be thought of as part of a disparity minimisation strategy which is responsible for minimising torsional differences and thus the cyclodisparities between the images on the two retinae (Kertesz and Sullivan 1978; Howard and Rogers 1995).

It is important to note that if the eyes are misaligned in either a vertical or torsional direction, a single parameter describes the degree of vertical or torsional misalignment, and hence the signal required for nulling the disparities may be averaged over the pattern of disparities in the whole visual scene. (Strictly speaking, this is only true when the optic arrays at the vantage points of the two eyes are identical, ie when the

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visual scene consists of a plane at infinity.) In the case of horizontal vergence, on the other hand, the signal required to minimise the disparity of the to-be-fixated object is necessarily local and should not be averaged over an area greater than the to-be-fixated object. As a consequence, it should come as no surprise to discover that visual information from a wide field of view is used to align the eyes vertically and torsionally (Howard and Sun 1994; Howard et al 1997), but only the central area of the visual field is used to control horizontal vergence (Fang et al 1998; Popple et al 1998b).

A particular pattern of cyclodisparities is created by the torsional misalignment of the two eyes in which the magnitude of the cyclodisparity increases with radial eccentricity from the fovea (figure 1a). The circumferential cyclodisparities created by torsional misalignment are purely horizontal along the vertical meridian and purely vertical along the horizontal meridian of the eyes. Consequently, the visual system might average the circumferential component of the disparity field over all radial directions in order to provide a correction signal for cyclovergence. The empirical evidence shows that the cyclovergence system can have a gain of over 0.9 when stimulated with identical dichoptic patterns which rotate sinusoidally in opposite directions at low temporal frequencies (Howard and Zacher 1991). While averaging cyclodisparities over the whole visual field might be thought to be an optimal strategy, Rogers and Howard (1991) first showed that cyclovergence is not, in fact, driven equally by cyclodisparities in all radial directions from the fovea (see also Rogers 1992 and Howard and Rogers 1995). Instead, we found that while the pattern of vertical disparities created by stimuli which shear vertically in opposite directions in the two eyes was almost as effective in driving cyclovergence as counter-rotating patterns, the pattern of horizontal disparities created by stimuli which shear horizontally was quite ineffective (figure 2) (see also van Rijn et al 1992). Instead of averaging cyclodisparities over all radial directions to correct for torsional misalignment, it would appear that the visual system relies primarily on the

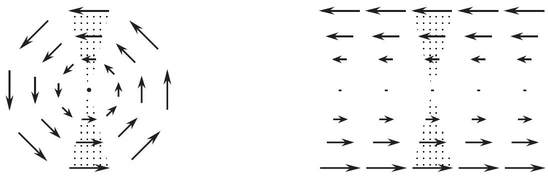

Figure 1. (a) The disparity (difference) vectors created when the image to one eye is rotated with respect to the other, as would happen when the eyes are torsionally misaligned. Note that binocular images which are related by a horizontal shear (b) create a similar vertical gradient of horizontal disparities about the vertical meridian as the rotation transformation. Hence, a vertical gradient of horizontal disparities about the vertical meridian is not an unambiguous indicator of the cyclovergence state of the two eyes.

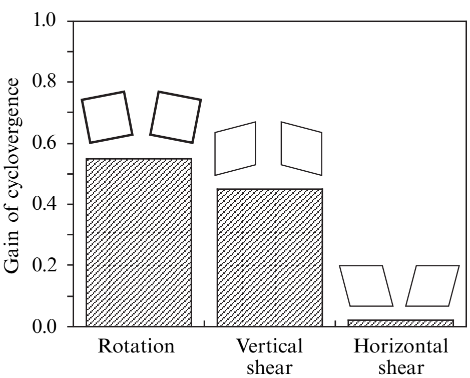

Figure 2. The gain of cyclovergence for dichoptic images which are related by an equal and opposite vertical shear has been found to be high and not much less than the gain for images related by an equal and opposite rotation. In contrast, the gain of cyclovergence for dichoptic images which are related by an equal and opposite horizontal shear has been found to be very low (Rogers 1992). This suggests that cyclovergence is mainly driven by the uniform horizontal gradient of vertical disparities created by both the rotation and vertical shear transformations. Mean of four subjects.

horizontal gradient of vertical disparities (which is created by a vertical shear as well as by torsional misalignment) and ignores the vertical gradient of horizontal disparities (which is created by both a horizontal shear and a torsional misalignment).

Why should the visual system decompose the cyclodisparity field in this way? Rogers (1992) pointed out that while the uniform horizontal gradient of vertical disparities along the horizontal meridian can only arise from torsional misalignment of the two eyes, a uniform vertical gradient of horizontal disparities is created by both a torsional misalignment of the two eyes and a surface inclined in depth (figure 1). Hence, the reliable signal for maintaining the torsional alignment of the two eyes is a uniform horizontal gradient of vertical disparities along the horizontal meridian which is unaffected by the 3-D characteristics of the visual scene. In this way, the disparities due to the irrelevant torsional misalignment of the two eyes can be eliminated and the pattern of horizontal disparities due to the scene structure is preserved and is uncontaminated by the effects of cyclovergence. Even if the oculomotor correction for torsional misalignment were incomplete, it would still be possible for the visual system to 'subtract out' (at a neural level) the torsional component of the disparity field (which can be inferred unambiguously from a uniform horizontal gradient of vertical disparities along the horizontal meridian), and thereby leave an 'uncontaminated' pattern of horizontal disparities.

In spite of the eye-movement evidence, Frisby et al (1993) proposed that the visual system might use cyclovergence in an attempt to minimise the overall pattern of both horizontal and vertical disparities as part of a strategy for minimising disparities. To test the hypothesis, their observers were presented with a visual scene consisting of a single surface subtending 20 deg $\times$ 20 deg, which was inclined in depth. Assuming that the eyes were initially aligned torsionally, the pattern of disparities created by an inclined surface is, to a first approximation, one of horizontal shear (figure 1b) (Rogers and Graham 1983; Rogers 1992). If the eyes were to counter-rotate by one half of the amount of the shear angle, the absolute magnitude of the horizontal disparities (and thus the vertical gradient of horizontal disparities) would halve at the expense of introducing a uniform horizontal gradient of vertical disparities of a similar magnitude. In this way, the largest absolute disparities, as well as the average of the unsigned disparities created by the scene, would be halved. To test the disparity minimisation hypothesis, Frisby et al attempted to measure the amount of cyclovergence created by a single inclined surface in depth.

To determine the cyclovergent state of the two eyes, Frisby et al used a dichoptic pair of vertically oriented nonius lines which were superimposed on the inclined surface. They found that the two nonius lines which were initially aligned (ie they would be seen as aligned if presented to a single eye) were perceived to have a different orientation in the presence of the inclined surface and to take on a chevron shape in appearance. The authors interpreted these results as showing that the eyes had made equal and opposite cyclovergent eye movements in the presence of the surface (figure 3b) and the reported degree of misalignment was close to 50% of the orientation disparity of the surface. Such a finding corresponds precisely to the prediction of the disparity minimisation hypothesis. But note that the results are inconsistent with those of Rogers and Howard (1991), who showed that a pair of images which are related by a horizontal shear (creating a vertical gradient of horizontal disparities) was very poor at driving cyclovergence (figure 2). The experiments carried out by Frisby et al and Rogers and Howard differed in two important respects and these differences may account for the different results. First, Frisby et al used a real, inclined surface whereas Rogers and Howard used dynamically changing images presented on frontal projection screens. Frisby et al suggested that horizontally shearing images presented on frontal plane projection screens in the Rogers and Howard study might have failed to produce a cyclovergent response because they were not created by a real 3-D surface. Second,

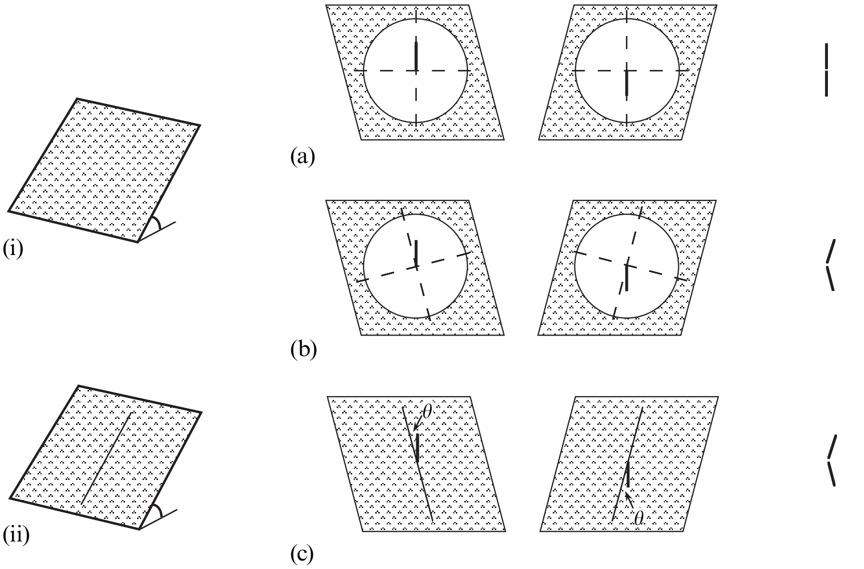

Figure 3. The binocular images created by an inclined surface (i) are related, to a first approximation, by a horizontal shear transformation (centre columns). The cyclovergent state of the eyes is indicated by the circular disc with the dashed horizontal and vertical meridia. If the eyes are initially aligned torsionally (a), dichoptic nonius lines which are physically vertical will be imaged on the vertical meridia of the two eyes and should therefore appear to be aligned (top right). If the inclined surface causes the eyes to cycloverge outwards (extort), the physically vertical nonius lines are no longer imaged on the vertical meridia and, as a consequence, they should appear to be at different orientations in the two eyes in the form of a chevron (b). On the other hand, if the eyes stay torsionally aligned but the nonius lines are seen as lying in the surface (ii), they should no longer appear to be aligned (as they are in the two eyes' images) but rather tilted with respect to corresponding features on the two surfaces (c).

Frisby et al measured the state of cyclovergence indirectly using nonius lines, whereas Rogers and Howard measured cyclovergence objectively using scleral contact lenses.

The aim of the experiments described in the present paper was to examine these two methodological differences in order to see if there was evidence for the disparity minimisation hypothesis proposed by Frisby et al. Separate conditions in experiment 1 replicated the viewing situations of both previous experiments so that the cyclovergence response to horizontally shearing stimuli (Rogers and Howard) could be directly compared to the cyclovergence response created by a real, inclined surface (Frisby et al). In experiment 1, cyclovergence was measured directly with the use of scleral contact lenses. In experiment 2, we examined the validity of using nonius lines as a technique for measuring the cyclovergence state. The stereogram in figure 4 has been prepared to demonstrate the potential problem of using nonius lines. The two random-dot images making up the stereogram are related by a horizontal shear and the two pairs of dichoptic nonius lines, which are physically vertical and horizontal, are superimposed onto the two images. When the stereogram is fused, a vivid impression of a plane inclined in a vertical direction should be seen. Careful inspection of the vertical nonius lines should reveal that they do not appear to be aligned but instead they appear to be slightly tilted in opposite directions, forming a chevron with its apex towards the left, when viewed with crossed-eyed fusion (cf figure 3). It was this apparent misalignment of the nonius lines that Frisby et al took as evidence that the eyes had cycloverged and hence the role of cyclovergence in a disparity minimisation process. However, readers should note that although the vertical nonius lines take on their chevron appearance, the horizontal nonius lines appear to remain horizontal and aligned.

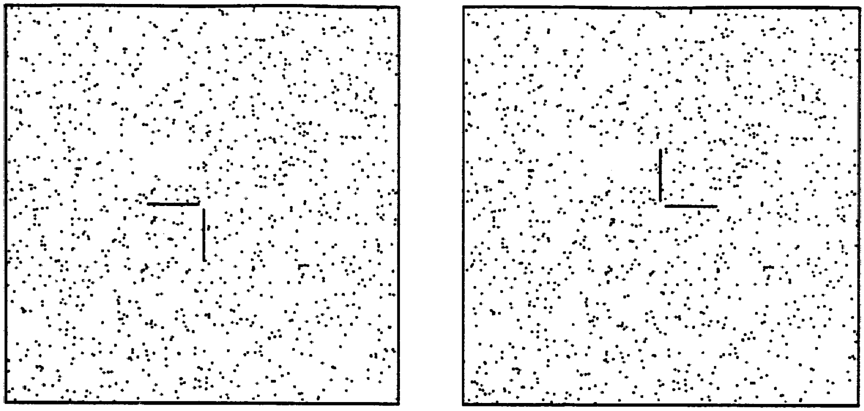

Figure 4. A random-dot stereogram in which the binocular images are related by a horizontal shear transformation. As a consequence, the fused stereoscopic image should be seen as a surface inclined in depth (a 'ground plane' with crossed-eyed fusion). The two pairs of dichoptic nonius lines superimposed on the stereogram are physically vertical and horizontal, but when seen against the inclined surface the vertical nonius lines should appear to be tilted with respect to each other as in a chevron. (The chevron appearance may not be seen until the full inclination of the surface is apparent after a few seconds.) In contrast, the horizontal nonius lines are physically aligned and should appear to remain aligned when seen against the inclined surface.

Ono (1993) and Ono and Mapp (1995) have shown previously that nonius lines do not always provide a valid measure of the horizontal vergence state (see also Shimono et al 1998). Using a random-dot stereogram which portrayed a centre disparate square with a crossed disparity, they found that, when observers fixated in the region of the centre square, a pair of superimposed nonius lines appeared aligned when they had an offset equal to the disparity of the centre square. Similarly, when observers fixated in the region of the surround, a second pair of superimposed nonius lines in that area appeared aligned when they had no offset. These results are not surprising and would normally be interpreted as indicating the observers' different vergence states when fixating the disparate centre square or the surround. The surprising result was that observers perceived the physically offset nonius lines in the centre square to be aligned when they fixated the surround and at the same time that the non-offset nonius lines in the surround also appeared to be aligned [see demonstration in Ono and Mapp (1995)].

Ono and Mapp proposed that this surprising finding is consistent with the idea that each pair of nonius lines is seen as lying in, and at the same depth as, its surrounding surface, even though each line is only seen monocularly. Erkelens and van Ee (1997a, 1997b) have proposed a similar idea to account for the capture of visual direction of monocular objects which are adjacent to binocular objects. As a consequence, nonius lines might not always be a reliable indicator of the horizontal vergence state if they are superimposed on, or closely surrounded by, a disparate surface. The parameters which affect the extent of influence of surrounding disparate surfaces on the appearance of nonius lines have been investigated recently by Shimono et al (1998). We refer to Ono and Mapp's explanation as the 'within surface' theory (Bradshaw and Rogers 1994). In contrast, Popple et al (1998a) have reported that nonius lines can still be a reliable indicator if they are presented after the 3-D surface has been removed. This suggests that nonius lines need to be either spatially or temporally separated from a surrounding disparate surface in order to be a valid indicator of horizontal vergence.

If the perceived Vernier offset of nonius lines can be influenced by the presence of a surrounding disparate surface, it occurred to us that the perceived orientational offset of a pair of nonius lines might be influenced by the presence of a surrounding inclined surface, in an analogous way. If this were true, nonius lines would not provide a valid measure of the cyclovergence state of the eyes. Exactly the same logic applies. If each of the monocular nonius lines is seen as lying in the plane of the inclined surface, the nonius lines will appear aligned when they have the same orientation disparity as that of the surrounding surface. Conversely, if the lines are both vertical and aligned in the image plane (figure 3c), they will appear to have different orientations if they are seen to be a part of the surrounding inclined surface. We suggest that this is the reason why the vertical nonius lines appear to have different orientations in figure 4 rather than the changed cyclovergence state of the two eyes.

The obvious test of the 'within surface' explanation of the tilted nonius lines is to use horizontally oriented nonius lines. The 'within surface' theory predicts that a pair of horizontally oriented nonius lines would still appear aligned when superimposed on an inclined surface whereas, if cyclovergence were responsible for the offset of the vertical oriented lines, a pair of horizontally oriented nonius lines would also appear to be tilted relative to each other and by a similar amount. (These predictions can be checked informally by looking at figure 4.) In experiment 2 we investigated these possibilities.

2 Experiment 1: Objective monitoring of cyclovergence in response to dichoptic horizontal image shear created by both real and simulated inclined surfaces

2.1 *Introduction*

The aim of the first experiment was to measure cyclovergence in response to both real and simulated inclined surfaces using objective eye-movement recording methods. We have shown previously that a continuous transformation consisting of an equal and opposite horizontal shearing to the two eyes does not lead to significant changes in cyclovergence (Rogers and Howard 1991; Rogers 1992). In those experiments, observers typically report that a horizontally shearing surface appears to change its inclination continuously like a surface rocking back-and-forth around a horizontal axis. However, it is possible that an equal and opposite horizontal shear (simulated inclination) is not as effective a stimulus for cyclovergence as the changing inclination of a real surface. This would account for why Frisby et al (1993) found cyclovergence changes in their experiment with real surfaces, whereas Rogers and Howard (1991) found little or no cyclovergence to simulated inclined surfaces. In the experiments reported here, the real inclined surface rocked back-and-forth around a horizontal axis at 0.1 or 0.05 Hz. The simulated surfaces were transformed at the same rates. Both displays subtended 20 deg $\times$ 20 deg as in the original study of Frisby et al. In order that the gains of cyclovergence to the real and simulated surfaces could be compared, we represented some of the other transforming dichoptic patterns used by Rogers and Howard (1991), including images which counter-rotated and images which sheared vertically by equal and opposite amounts in the two eyes. Moreover, we used the same observers in both parts of the experiment since we know that there are significant individual differences in the gain of cyclovergence (Howard and Zacher 1991; Rogers 1992). Two experienced psychophysical observers took part in the present experiment, one of whom was naïve to the purpose of the experiment.

2.2 *General methods*

2.2.1 *Recording equipment.* We recorded torsional eye movements using the system of field coils and close-fitting scleral contact lenses with embedded coils manufactured by Skalar of Delft. The lenses were individually calibrated with the aid of an artificial eye and were found to have gains of approximately 0.25 V/°. The noise level of the signals from the Skalar amplifiers was such that torsional eye movements of less than 1′ could be resolved. The six channels of the Skalar amplifier (horizontal, vertical, and torsional for both left and right eyes) were each monitored at a 250 Hz sampling rate by a Macintosh IIvi provided with a National Instruments AD interface board (Lab NB). The digitised signals were stored on disc for subsequent analysis and displayed as hard copy output.

The observers were asked to keep their eyes directed towards the centre of each stimulus which was marked by a small cross. Keeping the eyes in the primary positions minimises the possibility of significant crosstalk between the horizontal, vertical, and torsional signals (Robinson 1963).

2.2.2 *Real surfaces.* Observers were presented with a real inclined surface (20 deg in diameter), which oscillated sinusoidally back-and-forth around a horizontal axis between inclination angles of $-40°$ and $+40°$ to the vertical. The maximum orientation disparities that would be created by line elements lying on the inclined surfaces at $\pm 40°$ were 5.6 deg (± 2.8 deg in each eye).

The inclined surface oscillated back-and-forth through a motor and crank arrangement at either 0.1 or 0.05 Hz. The observer's line of sight was either horizontal and straight-ahead or, to replicate the viewing conditions of Frisby et al, the line of sight was inclined downward by 30°. To do this, the observer's head and the entire apparatus, including the coils which provide the magnetic field for the contact lenses, were all inclined downwards so that the observer's head remained in the centre of, and at the same orientation with respect to, the coils. The observer's line of sight remained orthogonal to the centre of the surface at the midpoint of its oscillation. In this way, any possible crosstalk between the horizontal, vertical, and torsional eye-movement recordings was minimised since the observer's eyes had the same visual direction with respect to the magnetic coils in both conditions. Each trial lasted for 60 s and eye movements were recorded continuously during that period. Two observers took part in the experiment, including one of the authors.

2.2.3 *Simulated inclined surfaces.* Observers were presented with coarsely textured patterns (element size $1-2$ deg) that were subjected to either (i) an equal and opposite horizontal shear, (ii) an equal and opposite rotation between the two eyes, or (iii) an equal and opposite vertical shear. The dichoptic visual images were rear-projected onto screens of translucent Mylar located to the left and right of the observer and viewed via a pair of front-silvered mirrors arranged as in a Wheatstone stereoscope.

The dichoptic displays were computer-generated image sequences (71 frames) and presented with two Electrohome EDP 58 video projectors driven by a Macintosh Quadra 950 at refresh rate of 67 Hz. Only 14 new images were presented every second but the small size of the displacement steps, together with the grey-level interpolation of the images, produced the impression of a smoothly transforming pattern. The images were circular with a diameter of 80 cm or 20 cm at the 57 cm viewing distance. The vertical shear, horizontal shear, or rotation transformation was modulated sinusoidally at a rate of either 0.1 or 0.05 Hz. The maximum amplitude of disjunctive cyclorotation in the displays was $\pm 2°$ of relative tilt. The disjunctive cyclorotation was the same at all orientations for the rotation transformation; it was maximal around the horizontal meridia for the vertically shearing patterns and maximal around the vertical meridia for the horizontally shearing patterns.

2.3 *Results*

The torsional-eye-movement traces for each of the two observers are shown in figure 5. The top row in each set of three traces depicts the torsional movements of the left eye, the second row the torsional movements of the right eye, and the bottom row in each set of three traces is the differences between the left and right torsional state and therefore indicates the extent of cyclovergence. Each trace is plotted against time (total 60 s). The first set of three traces (figure 5a) shows the torsional responses of each of the two observers to the real surface which changed its inclination continuously over time (gaze straight-ahead condition). The second set of three traces (figure 5b) shows the torsional eye-movement records when presented with dichoptic patterns

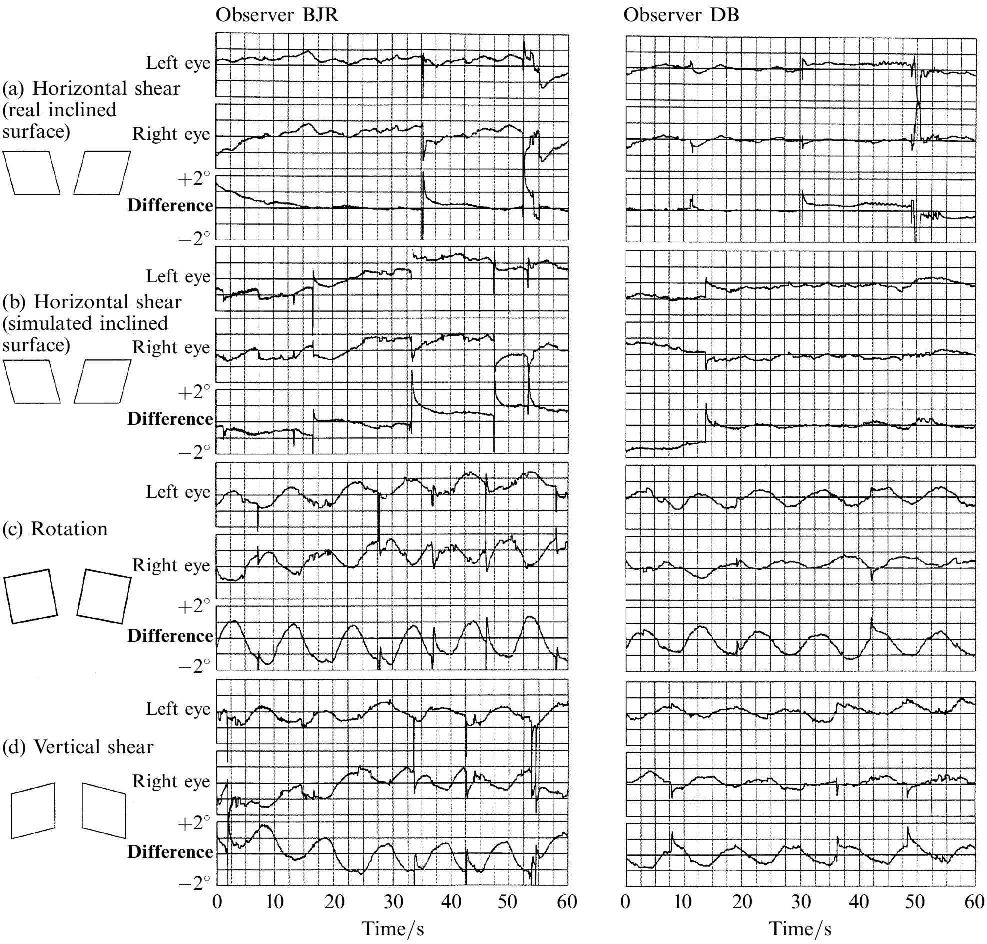

Figure 5. Recordings of torsional movements of the two eyes for each of the observers in response to the following stimulus transformations: (a) a real inclined surface which creates an equal and opposite horizontal shear transformation in the images reaching the two eyes; (b) an equal and opposite horizontal shear in the two eyes; (c) an equal and opposite rotation to the two eyes; (d) an equal and opposite vertical shear to the two eyes. The transformations were all at a temporal frequency of 0.1 Hz (period of 10 s). For each transformation, the upper of the three traces shows the torsional response of the left eye, the middle trace the torsional response of the right eye, and the lower trace the difference signal, indicating the extent of cyclovergence. Eye movements were recorded for a period of 60 s (abscissa). The important finding is the complete absence of cyclovergence to both the real inclined surface (first set of traces) and the simulated inclined surface (second set of traces) for both observers.

which were horizontally sheared to simulate the transformation created by a real inclined surface which changed its inclination. It is evident that the gain of cyclovergence (when measured objectively) is virtually zero for both the real surface which changed its inclination over time and the simulated inclined surface. In fact, the gain of the cyclovergence in response to the real-world inclined surface, averaged over the two observers and two different gaze conditions (with horizontal gaze, looking straight-ahead, and with head inclined downward), was negligible ($\sim 1\%$).

The third set of eye-movement traces (figure 5c) shows the torsional response to dichoptic patterns which counter-rotated in opposite directions. Here the difference signal clearly follows the equal and opposite rotation in 10 s cycles (0.1 Hz) as the stimuli counter-rotated in and out of alignment in the two eyes. The gain of the cyclovergence, averaged over the two observers, was about 25%. It is likely that the lower gains of cyclovergence to counter-rotating patterns found here are a consequence of the smaller (20 deg diameter) displays used in the present experiment compared to the large (70 deg) displays used by Rogers and Howard (1991) and Rogers (1992). These counter-rotating patterns provide a useful control, since the lack of cyclovergence in response to the real inclined surface or the horizontal shear transformation cannot be attributed to the poor cyclovergent response in our particular observers or to other artifacts such as the slippage of the contact lenses. Both observers showed significant and substantial cyclovergence in response to counter-rotating visual patterns at temporal frequencies of 0.1 and 0.05 Hz.

The fourth set of eye-movement traces (figure 5d) shows the torsional response to dichoptic patterns which were vertically sheared by equal and opposite amounts to the two eyes. The difference trace in the third row shows the extent of cyclovergence to vertical shear which, although slightly reduced in amplitude compared with the counter-rotating patterns for both observers, still shows a substantial cyclovergence response.

The results from all the conditions of experiment 1 are summarised in figure 6. Counter-rotation and equal and opposite vertical shear, which both create a horizontal gradient of vertical disparity, are capable of driving cyclovergence, as previously reported (Rogers and Howard 1991; Rogers 1992). The average gain was between 20% and 30%. The average gain of cyclovergence when the images sheared vertically was ~⅔ of the gain to counter-rotating patterns. This result is also consistent with previous findings. In contrast, a pair of dichoptic images transformed by an equal and opposite horizontal shear in the two eyes produced little or no cyclovergence, whether the transforming images were created by a real inclined surface which changed its inclination or by a pair of dichoptic and horizontally sheared images projected onto a frontal screen.

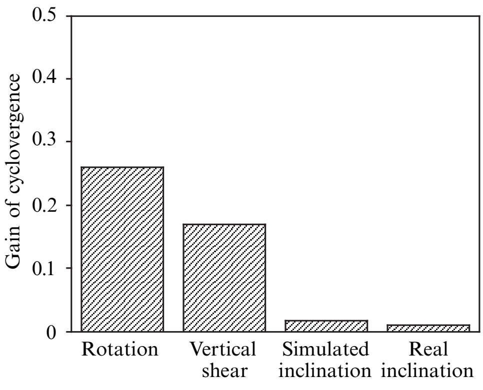

Figure 6. The histograms show the gain of cyclovergence, averaged over the two observers, to the four different transformations: rotation, vertical shear, horizontal shear, and the oscillations of a real inclined surface from experiment 1.

2.4 *Discussion*

The torsional-eye-movement recordings obtained in experiment 1 with dichoptic images which were transformed by an equal and opposite (i) rotation, (ii) vertical shear, and (iii) horizontal shear are all consistent with the eye-movement records reported by Rogers (1992) with similarly transforming stimuli. Rotation and vertical shear both drive cyclovergence while horizontal shear is almost completely ineffective. More important, the amount of cyclovergence in response to the real-world surface which changed its inclination (and thus also created a pattern of horizontal image shear to the two eyes) was negligible and comparable in magnitude to that produced by the horizontal shearing images which simulate an inclined surface. This result, which was obtained with the use of an objective measure of the cyclovergence state of the two eyes, is in contrast to the findings of Frisby et al (1993) who reported that a real inclined surface did produce cyclovergence. Frisby et al, however, measured cyclovergence indirectly with vertically oriented nonius lines.

3 Experiment 2: Assessing the validity of using nonius lines to infer the cyclovergence state of the eyes

3.1 *Introduction*

Frisby et al inferred the relative torsional state of the two eyes—cyclovergence—by measuring the degree of apparent misalignment of vertically oriented nonius lines. The stereogram in figure 4 illustrates the fact that, when vertically oriented nonius lines are superimposed on the two halves of a stereogram related by horizontal shear, they do appear misaligned. The validity of this measurement technique is assessed in our second experiment.

The explanation of why nonius lines might appear misaligned when the eyes cycloverge is straightforward. In figure 3a, the vertical and horizontal meridia of the two eyes (shown as dashed lines) are superimposed on top of a pair of horizontally sheared and textured images. In the top panel, when there is no cyclovergence, the nonius lines (in bold) lie on the vertical meridia of the two eyes, and so should be perceived as aligned and vertical in the absence of any other visible points or surfaces.

If, however, the eyes counter-rotate (cycloverge), as shown in the second row, an orientation difference is created between the physically vertical nonius line and the tilted vertical meridian in each eye (figure 3b). Hence, the perceived orientation of the nonius lines would change and they should appear as tilted in opposite directions in the form of a chevron as depicted on the right.

There is, however, an alternative explanation, which we call the 'within surface' explanation (after Ono and Mapp 1995). Consider a surface inclined around a horizontal axis. A line drawn on that surface from top to bottom would also be sheared in the images in the two eyes (figure 3c). In other words, a line on an inclined surface creates an orientation disparity. Once fused, this line would appear to slope away from the observer like the surface itself. The situation is no different if the line is only visible to one eye for part of its length. For the line to be seen as straight and continuous over an inclined surface, each of the monocular elements making up the nonius line would have to have the same orientation difference as any line which is seen by both eyes. Therefore, if the monocular nonius lines are seen lying on the inclined surface (which is why we refer to it as the 'within surface' explanation), they would have to have an orientation difference between them. Conversely, if the lines are physically vertical and aligned in the image plane, they should appear to be tilted relative to each other (in the form of a chevron) since only lines which are *not* aligned on an inclined surface would create a pair of images which are aligned in the image plane (figure 3c).

Note that both explanations predict that vertically oriented nonius lines should appear misaligned in the same direction. Quantitatively, the cyclovergence explanation predicts that the amount of misalignment should be the same as the amount of cyclovergence, whereas the amount of misalignment predicted by the 'within surface' explanation depends on the extent to which the lines are seen as 'lying in the surrounding inclined surface'. There are, however, circumstances in which the two explanations give different predictions.

In the first part of experiment 2, pairs of either vertically or horizontally oriented nonius lines were superimposed on pairs of stereoscopic images related by a horizontal shear transformation and the degree of misalignment of the nonius lines was measured. If the eyes cycloverge to the horizontally sheared patterns, both the horizontal and vertical nonius lines should appear to be misaligned in the same direction and by the same amount. However, if the apparent misalignment of the vertical nonius lines in the experiment of Frisby et al were due to the lines being seen 'within the surface', there should be no apparent misalignment of the horizontal nonius lines.

In the second part of experiment 2, either horizontal or vertical nonius lines were superimposed on pairs of stereoscopic images related by a vertical shear transformation, which we know from experiment 1 and previous research to be capable of driving cyclovergence. In this case, the nonius lines were superimposed on the stereoscopic images before the shearing transformation was applied. As a consequence, the horizontal nonius lines were misaligned in the stimulus whereas the vertical nonius lines were vertical and aligned. With horizontal nonius lines superimposed on stereoscopic images related by a vertical shear, both explanations of the nonius misalignment predict that during cyclovergence (i) the horizontal nonius lines should gradually become realigned as the horizontal meridia of the eyes rotate until they coincide with the misaligned nonius lines, and (ii) there may be a simultaneous increase in the amount of perceived inclination as the physically vertically sheared images are transformed into horizontally sheared images on the retinae of the cycloverged eyes (Cagenello and Rogers 1991; Rogers 1992). With vertical nonius lines, the predictions of the two explanations differ. According to the cyclovergence explanation, the physically vertical nonius lines should appear to become successively more *misaligned* as the eyes rotate since the vertical nonius lines will no longer coincide with the vertical meridia of the eyes as the eyes cycloverge. On the other hand, the 'within surface' explanation predicts that the lines should stay aligned throughout the build-up of slant because the relative position of the nonius lines, with respect to the features on the surface, should not be affected by cyclovergence if they are perceived to lie within the surface.

As a consequence, we have different predictions for the two explanations in two different situations. In the case of horizontally sheared images (where cyclovergence does not occur when measured objectively), the two explanations make different predictions about the apparent alignment of *horizontally* oriented nonius lines. In the case of vertically sheared images (where experiment 1 shows that cyclovergence does occur), the two explanations make different predictions about the apparent alignment of *vertically* oriented nonius lines.

3.2 *Methods*

The observer's task in experiment 2 was to judge the apparent alignment of either vertically or horizontally oriented nonius lines. The nonius lines in both cases were superimposed on a pair of stereoscopic images related by either a horizontal or a vertical shear. The stimuli were presented to observers on two large display oscilloscopes (HP 1304A) at a distance of 57 cm. The two monitors were viewed independently by the two eyes via two sets of mirrors in a modified Wheatstone configuration (Rogers and Graham 1982). Disparities between the two images were created electronically by introducing equal and opposite shifts to the patterns of dots on the two display screens. Since the displacement signal which created the disparities was a continuous analogue waveform, the pixels could be displaced by any arbitrary fraction of the pixel separation so that the disparity modulation was smooth and continuous. To create a pair of stereoscopic images related by a horizontal shear, an equal and opposite ramp waveform was applied to the horizontal deflection of the two displays. To create a pair of stereoscopic images related by a vertical shear, an equal and opposite ramp waveform was applied to the vertical deflection of the two displays. The stimuli were 50% random-dot patterns of 240×240 pixels, visible within a circular aperture of 20 deg diameter. Dot separation was 5 min of arc.

For the trials in which the observers were presented with stereoscopic images related by a *horizontal* shear, the relative orientation of the pair of nonius lines was under the control of the observer. Adjustment of a potentiometer created an equal and opposite relative tilt in the nonius lines and the observer's task was to adjust the apparent orientations of the two nonius lines continuously to keep them as aligned as possible. Adjustment settings were recorded both when the stereograms depicted surfaces with an inclination of $+45°$ from the frontal plane ('ground planes') and when they depicted surfaces with an inclination of $-45°$ from the frontal plane ('sky planes').

For the trials in which the observers were presented with stereoscopic images related by a *vertical* shear, observers were also required to give verbal estimates of the apparent inclination of the surface over time. For technical reasons it was impossible to superimpose adjustable nonius lines on the vertically sheared images and as a consequence observers were asked to report the apparent alignment of the nonius verbally. Their responses were transcribed as a function of the time elapsed from the start of the trial. Six observers participated in the experiment, four of whom were completely naïve as to its purpose.

3.3 *Results*

3.3.1 *Horizontally sheared images.* The nonius line settings when the lines were superimposed on stereoscopic images related by a horizontal shear are shown separately for the 'ground' and 'sky' plane surfaces in table 1.

Table 1. The average orientation setting (six observers) of the nonius lines (oriented either vertically or horizontally) for the lines to appear collinear together with the standard errors. Results are expressed as a percentage of the orientation disparity of the $\pm 45°$ inclined surfaces against which the lines were seen. Note the striking difference between the results for the vertical and horizontal nonius lines.

	Vertical nonius line		Horizontal nonius line	
	ground	sky	ground	sky
Orientation disparity/%	23.2 ± 4.2	14.3 ± 1.8	1.5 ± 0.5	1.1 ± 0.4

The most striking result is that the misalignment was much greater when vertical nonius lines were used than when horizontal lines were used—an average of 19% of the orientation difference between the images for vertical nonius lines compared with $\sim 1\%$ of the orientation difference for horizontal nonius lines. If Frisby et al were correct in assuming that cyclovergence was responsible for the misalignment of the vertical nonius, the amount of nonius misalignment should have been the same for both the vertical and horizontal nonius lines. It is clearly different.

For the vertically oriented nonius lines, the 'within surface' theory predicts that the apparent misalignment should be 100% of the orientation difference created by horizontally sheared images if the nonius lines are seen as lying at the same inclination as the surface. Subjective reports obtained during the experiment indicated that observers did not always see the vertical nonius lines as lying at the same inclination as the surface and this is likely to be the reason why the average perceived misalignment was only 19%. However, this under-prediction should not detract from the main result which is that *only* vertical nonius lines were influenced by horizontally sheared images—a result that is inconsistent with an explanation based on cyclovergence.

3.3.2 *Vertically sheared images.* In the second part of the experiment, two of the observers were asked to estimate the perceived slant and the perceived misalignment of the nonius lines while viewing stereoscopic images related by a vertical shear. The results of this experiment are shown in figure 7.

The upper halves of the two graphs show the gradual build-up in perceived inclination of the vertically sheared images, which is consistent with the fact that the eyes made cyclovergent movements over time. On the trials in which the superimposed nonius lines were *horizontal* (a), the lines were at first seen to be markedly misaligned (as they were in the physical images) but gradually, as the surface appeared to become more slanted, the horizontal nonius lines appeared to become more aligned. On the trials in which the superimposed nonius lines were *vertical* (b), observers reported the same build-up of apparent inclination over time, but this time the nonius lines remained

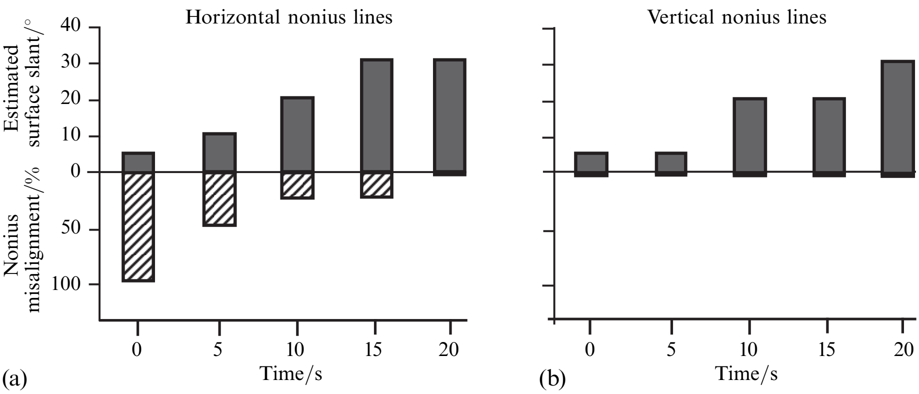

Figure 7. The lower histograms show the estimated degree of misalignment (average of the two observers' results) of either horizontally oriented nonius lines (a) or vertically oriented nonius lines (b) as a function of the time elapsed after the onset of the dichoptic, vertically sheared images. The horizontally oriented nonius lines in (a) initially appeared to be misaligned (as they were in the vertically sheared images) but over the course of 20 s they became more aligned. The vertically oriented nonius lines in (b), however, remained aligned over the 20 s time course. The latter result is consistent with the nonius lines being seen as lying within the inclined surface but is inconsistent with the cyclovergence explanation. For both orientations of the nonius lines, the inclination of the vertically sheared images built up over time (upper histograms).

completely aligned throughout. This result is inconsistent with an explanation based on cyclovergence but is consistent with the 'within surface' explanation.

3.4 *Large-field surfaces—a final test*

It could be argued that our failure to find evidence for cyclovergence, either objectively by using scleral search coils or indirectly with horizontally oriented nonius lines (which are not affected by the inclination of the surrounding surface), might be due to the small angular size of our real and simulated inclined surfaces (20 deg). We know that the largest gains for cyclovergence are obtained for patterns which fill a large portion of the visual field (Howard and Sun 1994) and in the present study we recorded gains of only 25% to counter-rotating patterns with the 20 deg diameter displays. To test this possibility, we optically superimposed horizontally oriented nonius lines onto a real textured and inclined surface which subtended nearly 80 deg $\times$ 80 deg of visual angle. (We chose the 20 deg diameter surface in experiment 1 because that was the size of the real inclined surface used in the experiment of Frisby et al 1993.) The inclination of the 80 deg surface was set at six different values between 0° (frontal plane) and 80° of ground plane inclination. Observers used a nulling procedure to adjust the relative tilt of the optically superimposed nonius lines until they appeared to be aligned. The dichoptic nonius lines extended from the centre of the surface to its extremities.

The pattern of results was the same as in experiment 2 (figure 8). Horizontally oriented nonius lines appeared to be aligned when they were aligned in the image plane, indicating that the eyes had not cycloverged for any of the inclination angles. The average null setting for four observers was less than 0.5° from physical alignment. This result reinforces our conclusion that cyclovergence is not initiated by inclined surfaces even when the surface fills a large proportion of the visual field. The amount of cyclovergence predicted by the disparity minimisation hypothesis is shown in figure 8 for comparison.

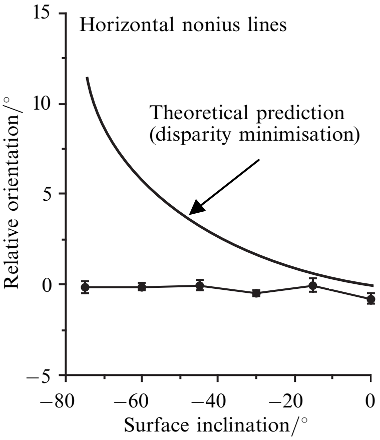

Figure 8. In the final experiment, four observers adjusted the relative orientation of horizontally oriented nonius lines superimposed on a large-field inclined surface which subtended 80 deg × 80 deg. The average of the observers' settings (closed circles) for all angles of inclination up to 80° were consistent and close to zero providing no evidence that the eyes had cycloverged. The error bars show the standard errors of the means. The prediction of the disparity minimisation hypothesis, in which the eyes make cyclovergent movements to an extent of 50% of the maximum orientation disparity created by the surface, is shown by the continuous line.

4 Discussion

The results of our experiments do not support the claim of Frisby et al (1993) that cyclovergence can be elicited by the binocular horizontal image shear created by a real inclined surface. We have replicated their viewing conditions and found little or no cyclovergence when the torsional states of the two eyes were measured objectively. This was true for both real inclined surfaces and for the simulated inclination based on the horizontal shear between images projected onto frontal projection screens. We attribute the 'cyclovergence' in response to real inclined surfaces reported by Frisby et al to an artifact in the use of nonius lines first identified by Ono (1993) with respect to horizontal vergence movements. The previous literature also suggests that nonius lines may not always be a valid member of determining the state of cyclovergence. Howard et al (1993), for example, noted that there were discrepancies between the state of cyclovergence inferred from nonius lines and direct measurements of cyclovergence with scleral search coils (see also Kertesz 1983).

In the present experiments we found that a real inclined surface did not elicit a cyclovergence response, which is consistent with the results of previous experiments with simulated inclined surfaces based on pairs of images related by a horizontal shear (Rogers and Howard 1991). A strong test of the cyclovergence explanation can be made by using nonius lines of different orientations, since this explanation predicts that the orientation of nonius lines should have no effect on the results. This was not found to be the case. Instead, whilst vertical nonius lines superimposed on an inclined surface showed a misalignment consistent with the results of Frisby et al, horizontal nonius lines were unaffected. We interpret this result as a consequence of seeing the vertical nonius lines as superimposed or 'within' the inclined surface (at least to some degree). The results of experiment 2 are consistent with the 'within surface' explanation both in situations where cyclovergence took place (vertical shear) and in situations in which it was negligible (horizontal shear). Moreover, the results are inconsistent with an explanation based on a change of cyclovergence.

We conclude that the average gain of cyclovergence of nearly 50% reported by Frisby et al (1993) for real inclined surfaces was not due to cyclovergence but rather to an artifact created by the nonius measurement technique they used. As a consequence, we find no evidence to suggest that the human visual system minimises the overall pattern of horizontal and vertical disparities created by an inclined surface in the manner proposed by Frisby et al. Moreover, our experiments reveal the important finding that nonius lines may not alway be a valid method for measuring the cyclovergence state of the two eyes when there are other surfaces behind or immediately surrounding the nonius lines.

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