

The effects of eccentricity and vergence angle upon the relative tilt of corresponding vertical and horizontal meridians revealed using the minimum motion paradigm

Timothy Ledgeway[¶], Brian J Rogers

Department of Experimental Psychology, University of Oxford, South Parks Road, Oxford OX1 3UD, UK
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Abstract. When the corresponding horizontal meridians of the two eyes are aligned, the corresponding vertical meridians are tilted outwards in a temporal direction, a phenomenon first described by Helmholtz. However, it is not known if this effect is confined to the principal meridians or whether the same relationship exists between corresponding horizontal and corresponding vertical meridians at eccentric retinal locations. We sought to address this issue by exploiting the technique of Nakayama (1977 *Proceedings of the Society of Photo-Optical Instrument Engineers* **120** 2–9) in which the positions of alternating dichoptic images that produce minimal apparent motion were used to measure the relative tilt of corresponding meridians at a range of eccentricities up to ± 16 deg away from the fovea. Stimuli were composed of dichoptic images, one containing a blank field and the other a pair of dots, which alternated at a rate of 0.63 Hz and the relative tilt (binocular orientation difference) between the pairs of dots presented to the two eyes was varied between $\pm 11^\circ$. Nonius lines were used to maintain vergence angle, which was varied between 28 cm and infinity. Subjects judged which pair of alternating images produced the smallest amount of apparent motion (position change). It was found that at all eccentricities examined the corresponding horizontal meridians were generally aligned but the corresponding vertical meridians were consistently offset (extorted) by about $\pm 2^\circ$. The tilts of corresponding principal meridians were typically unaffected when vergence angle was varied, indicating that little or no cyclovergence accompanied changes in horizontal vergence. The results suggest that the binocular correspondence system appears to be mapped by a horizontal shear distortion that extends to retinal locations at least as far as 16 deg away from the fovea. The invariant extorsion of corresponding principal vertical meridians with vergence state is consistent with previous suggestions that the empirical vertical horopter becomes progressively inclined with respect to the vertical as viewing distance increases.

1 Introduction

Binocular visual systems with overlapping visual fields are able to exploit stereoscopic information by virtue of the fact that images falling upon two horizontally separated retinas are slightly different. Wheatstone (1838) was the first to demonstrate that these differences or disparities between the images presented to the two eyes provide important information concerning relative depth in the visual scene and form the basis for our perception of three-dimensional space. However, it has been recognised for centuries (eg Aguilonius 1613) that not all images that fall on the two retinas are disparate and it is possible, given certain assumptions, to map out the positions in space that would stimulate retinal regions that are in binocular correspondence (the theoretic or geometric horopter). For example, if the two retinas are considered congruent, then images falling upon corresponding retinal points, such as the centres of each fovea, have zero binocular disparity and appear to have a single visual direction in space. Conversely, images that fall upon noncorresponding points are disparate and have different monocular visual directions in the two eyes. Therefore, the concept of binocular correspondence is crucial both to the definition of disparity and also for an understanding of how the visual system may encode stereoscopic information.

[¶]Present address: McGill Vision Research, Department of Ophthalmology, McGill University, 687 Pine Avenue West, Room H4-14, Montreal, Quebec H3A 1A1, Canada

Research on binocular correspondence has tended to focus on the geometry of one or more forms of the theoretical horopter such as the point horopter which is the locus of points in space which stimulate corresponding retinal points. For the case in which the two eyes are symmetrically converged in the horizontal plane, the theoretical horizontal horopter is the Vieth–Müller circle which passes through the nodal points of the two eyes and the point of fixation. The vertical horopter is a single vertical line which passes through the Vieth–Müller circle at the point of fixation. However, it is also possible to define the horopter in terms of entities (eg extended lines, retinal meridia) other than retinal points provided that the constraint that disparity is zero in both the horizontal and vertical dimensions is relaxed (see Howard and Rogers 1995).

Measurements of the empirical horizontal horopter (eg Ames et al 1932a, 1932b; Shipley and Rawlings 1970a) have been carried out by a variety of psychophysical techniques, such as positioning a number of vertical lines or rods so that they appear to lie in the frontal plane, or setting a pair of vertically oriented nonius lines so that they appear collinear, and have common monocular visual directions. Although there appears to be some deviation (eg the well-known Hering–Hillebrand deviation) of the empirical horizontal horopter from the Vieth–Müller circle, considerable individual differences between observers and a lack of consensus over the interpretation of the results, especially those derived from judgments of the apparent frontal plane, have led to considerable confusion regarding the form of the empirical horizontal horopter (for a review see Shipley and Rawlings 1970b).

Measurements of the empirical vertical horopter have received much less attention than those of the horizontal horopter, despite the fact that observations by Helmholtz (1910/1962) who used nonius lines suggested that, when the principal horizontal meridia of the two eyes are aligned, the corresponding principal vertical meridia are tilted outwards (extorted) by approximately $\pm 1^\circ$. This suggests that the empirical vertical horopter is not in fact a vertical line, but rather a line that is inclined top-away from the observer in the median plane and passes through the fixation point. More recent studies (eg Nakayama et al 1977; Cogan 1979) have also led to the conclusion that the corresponding principal vertical meridia are indeed extorted but to a greater extent than that originally estimated by Helmholtz. For example, Nakayama (1977) employed a minimum apparent motion technique, developed by Flom (1957), in which the horizontal positions of alternating dichoptic points that produced minimal interocular apparent motion were assumed to stimulate retinal points lying on corresponding vertical meridia. He found that, for a range of elevations in the visual field of up to ± 30 deg, the corresponding principal vertical meridia of the two eyes were tilted outwards in opposite directions by about $\pm 2^\circ$ from the vertical. Similar measurements of the corresponding principal horizontal meridia showed that they were approximately aligned, indicating that the extorsion of the vertical meridia was not due to excyclovergence (opposite torsional rotation) of the two eyes. Extorsion of the corresponding principal vertical meridia has been demonstrated electrophysiologically in some species of mammals and birds (Cooper and Pettigrew 1979) and it may also account for an anisotropy reported in the psychophysical literature (Breitmeyer et al 1976) concerning the locus of best stereoscopic vision. For example, Julesz et al (1976) found, using dynamic random-dot stereograms, that the duration required for the detection of a small stereoscopically defined target located centrally in the visual field was shortest when the target was located either in front of and below or behind and above the fixation point. This upper–lower visual field anisotropy is interesting in that the locations of the regions of best detection performance coincide closely with the location of the inclined empirical vertical horopter.

If these phenomena are indeed indicative of the locus in space of the empirical vertical horopter, then this has a number of important implications for understanding binocular

correspondence. First, it suggests that the corresponding principal vertical meridians are sheared horizontally with respect to the corresponding principal horizontal meridians. Although in all previous studies measurements have been made along the principal meridians, it is possible that the same relationship exists between corresponding horizontal and corresponding vertical meridians in eccentric retinal locations. This would imply that the entire binocular correspondence system is mapped by a horizontal shear distortion. Although objects in space that are not positioned in either the median plane of the head or the horizontal plane containing the Vieth–Müller circle give rise to images that do not fall upon geometrically corresponding points, there must be positions in space that give rise to retinal images that are closest to falling on corresponding points. The patterns of empirical correspondence in eccentric locations have been examined in several previous studies with variations of the minimum motion paradigm employed by Nakayama (1977). For example, Rogers and Bradshaw (1996) investigated whether or not the human visual system takes advantage of the epipolar constraint in determining correspondence between retinal images, and Banks and Backus (1998) have looked at the shape of the most fusible surface. The epipolar constraint refers to the fact that, provided that the two eyes are torsionally aligned, all the potential matches for an image element in one eye must fall along an epipolar line in the other eye. This simplifies the search for matching corresponding images to that of a one-dimensional search. It is important to note that epipolar lines are defined with respect to the axis joining the two eyes, and are retinal meridians that pass through the poles of the interocular axis. Consequently the pattern of retinal correspondence would be expected to vary in a systematic manner with vergence angle (viewing distance) and, in order to make use of this constraint in human vision, non-optical information concerning the relative positions of the two eyes must be known. Rogers and Bradshaw found evidence to suggest that to a certain extent this is actually the case. They employed alternating dichoptic images containing a pair of vertically separated horizontal lines with a variable binocular orientation difference between the images presented to the two eyes and adjusted their relative orientation until observers reported the least amount of interocular apparent motion between the lines. They found that for a range of vergence angles the pairs of images observers selected tended to be consistent with the use of the epipolar constraint. For any given vergence angle, the pair of images producing minimum apparent motion had an orientation difference close to zero such that the lines were approximately horizontal on the planar projection screens. This would suggest that in eccentric retinal locations empirically corresponding horizontal meridians remain approximately horizontal (with respect to the interocular axis) with changes in vergence angle.

Second, a number of authors, including Helmholtz, have pointed out that, if the relative tilt of the corresponding principal vertical meridians is constant with fixation distance, then for close viewing distances the empirical vertical horopter is almost a vertical line, but as viewing distance increases the inclination of the horopter line increases such that it is horizontal at infinity. This implies that the horizontal shear of the corresponding principal vertical meridians has some ecological significance in that it brings the vertical horopter into alignment with the ground plane, upon which lie many of the objects of interest in the visual world (Banks and Backus 1998). However, the assumption that the relative tilt of the corresponding principal vertical meridians remains constant with large changes in fixation distance may not be valid, especially as cyclovergence may accompany changes in horizontal vergence (eg Nakayama 1983). In the present experiment we sought to address these two issues by exploiting the minimum motion paradigm of Nakayama (1977) to measure the tilt of corresponding vertical and corresponding horizontal meridians at (i) a range of eccentricities up to ± 16 deg and (ii) at a range of viewing distances (vergence angles).

2 Methods

2.1 Observers

Three observers participated in the study and all had normal or corrected-to-normal visual acuity. Observers TL and BJR were the authors, and observer MLG was a volunteer who was unaware of the purpose of the experiment.

2.2 Apparatus and stimuli

The observer was seated within a large-field (70 deg \times 70 deg square) Wheatstone stereoscope. Visual stimuli were generated by a Macintosh computer and presented by means of two Electrohome video projectors which projected the images in the left and right eyes onto two planar Mylar screens situated 57 cm from the observer's eyes. Stimuli were viewed dichoptically by means of two full-silvered mirrors at $\pm 45^\circ$. Volkman discs (outer diameter 3 deg, containing a small binocular horizontal line and dichoptic vertical nonius lines, were used to maintain horizontal, vertical, and torsional alignment of the two eyes which were always held in the primary position.

Dichoptic images, one containing a blank field and the other a pair of bright dots (diameter 3 deg) separated either horizontally or vertically by 42 deg, were alternated at a rate of 0.63 Hz to produce interocular apparent motion (shown schematically in figure 1a as an alternation between the top pair and the bottom pair of half-images). The dots in each monocular image had an absolute tilt with respect to either the horizontal or vertical of up to $\pm 5.5^\circ$ that was antagonistic between the two eyes (equivalent to a binocular orientation difference) such that the dots presented to the left eye were always tilted by the same amount as those presented to the right eye but

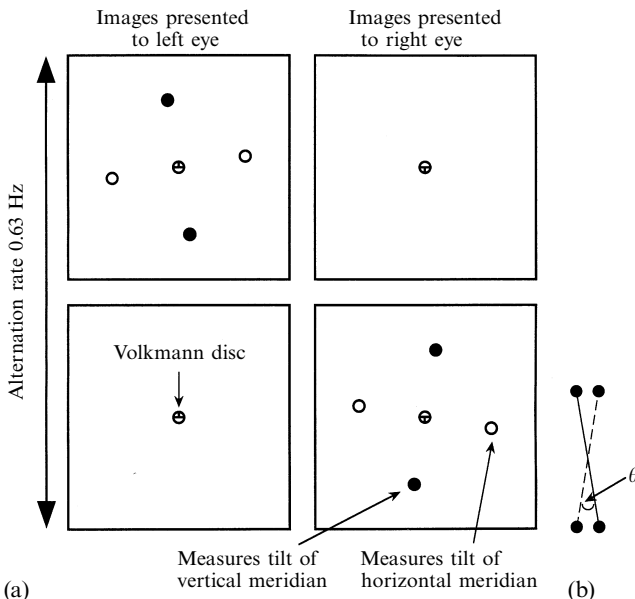


Figure 1. (a) Schematic diagram of the fixation stimuli and alternating dichoptic images used to measure the degree of alignment of corresponding meridians. To measure the relative tilt of corresponding vertical meridians a pair of monocular dots (shown as filled circles) separated vertically by 42 deg was presented to one eye and a blank field (except for the fixation stimulus) was presented simultaneously to the other eye, and the two images were alternated at a rate of 0.63 Hz to create interocular apparent motion. For measurements of the horizontal meridians the dots (shown as unfilled circles) were separated horizontally, rather than vertically, by 42 deg. Only one pair of dots, separated either horizontally or vertically, was displayed on any given trial. The dots had an equal but opposite tilt between the two eyes and the magnitude of this tilt was adjusted by the observer. (b) The dot positions at which the perception of apparent motion (spatial displacement) was minimal were used to calculate the relative tilt (θ) of corresponding meridians.

in the opposite direction. The magnitude of the relative tilt (angular difference in absolute tilt, θ , as shown in figure 1b) between the dot pairs presented to the two eyes was under control of the observer and could be increased/decreased (by displacing the dots by an integer number of pixels) in steps of about $26'$ by means of a potentiometer which was connected to the computer via an analogue-to-digital converter. The smallest change in relative tilt (angular resolution) possible was approximately inversely proportional to the dot separation. A dot separation of 42 deg was used in order to provide an adequate resolution of $26'$ for the tilt measurements whilst ensuring that the dots were still clearly visible. With a smaller dot separation the same displacement of the dots in terms of screen pixels would produce a greater effective change in the relative tilt of the dots. However, for one observer (TL) a control condition was included, in which the dot separation was reduced to 21 deg in order to verify that the results found in the main experiment were not limited to the particular choice of dot separation used (see section 3.2).

The retinal eccentricity of the dots in each image was manipulated by shifting the positions of both dots in the same direction (either horizontally or vertically) relative to the fixation point by a distance equivalent to either 0 , ± 2 , ± 4 , ± 8 , or ± 16 deg. The dot pairs were moved to different horizontal eccentricities when the dots were above and below the fixation point and were moved to different vertical eccentricities when the dots were to the left and right of fixation. The vergence angle of the binocularly visible fixation stimulus was varied between 780 and 0 min of arc (simulating viewing distances between 28 cm and infinity).

2.3 Procedure

On each trial the observer was presented with an alternating dichoptic pair of images and was required to select, using the method of adjustment, the pair of images that produced the smallest amount of opposite apparent motion (interocular orientation change) of the two dots.⁽¹⁾ That is, the observer's task was to adjust the potentiometer until the stimulus appeared as a pair of stationary or near-stationary flickering dots. Trials were self-paced and observers were instructed to take as much time as was necessary for each potentiometer setting. The effects of retinal eccentricity and vergence angle (viewing distance) were measured in separate randomised blocks of trials, and within each block the order of presentation of trials containing either horizontally or vertically separated dots was also randomised. Each observer made a minimum of three settings for each condition examined. Prior to formal data collection all observers were given extensive practice trials in order to familiarise themselves both with the adjustment procedure and the criterion of minimal apparent motion.

⁽¹⁾ The choice of coordinate system for specifying orientation on the retinae affects what is considered to be 'horizontal' and 'vertical'. As previous studies (eg Rogers and Bradshaw 1996) have shown that the visual system can, to a limited extent, utilise the epipolar constraint for determining binocular correspondence, in the present study what is considered to be 'horizontal' on the retinae is any pair of dots that give rise to images that fall along epipolar meridians in the two eyes which form a set of horizontal reference lines. Provided that the eyes are symmetrically converged and torsionally aligned, a pair of horizontally aligned dots on the planar projection screen will create images that fall upon these horizontal (epipolar) meridians. Similarly, for the present purposes what is considered to be 'vertical' on each retina is any pair of dots that create images that fall on vertical meridians which pass through the north-south poles of the eyeball. This choice of coordinate system is, however, arbitrary as different coordinate systems can be related by a simple transformation (see Howard and Rogers 1995).

3 Results

For each observer the relative tilts of corresponding horizontal and corresponding vertical meridians were calculated from the mean dot positions that produced minimal apparent motion (figure 1b) at each eccentricity and vergence angle.⁽²⁾ As there were no systematic differences between the data obtained from opposing hemifields (eg vertical meridians located in the left and right halves of the visual field), they were combined and averaged for each eccentricity examined. All results are expressed in terms of the magnitude and direction of the relative tilt such that positive values indicate intorsion, negative values extorsion, and a value of zero indicates that the corresponding meridians were parallel (ie either both horizontal or both vertical).

3.1 The effects of retinal eccentricity

In figure 2 the relative tilts of corresponding horizontal and corresponding vertical meridians are plotted separately as a function of retinal eccentricity for each observer.

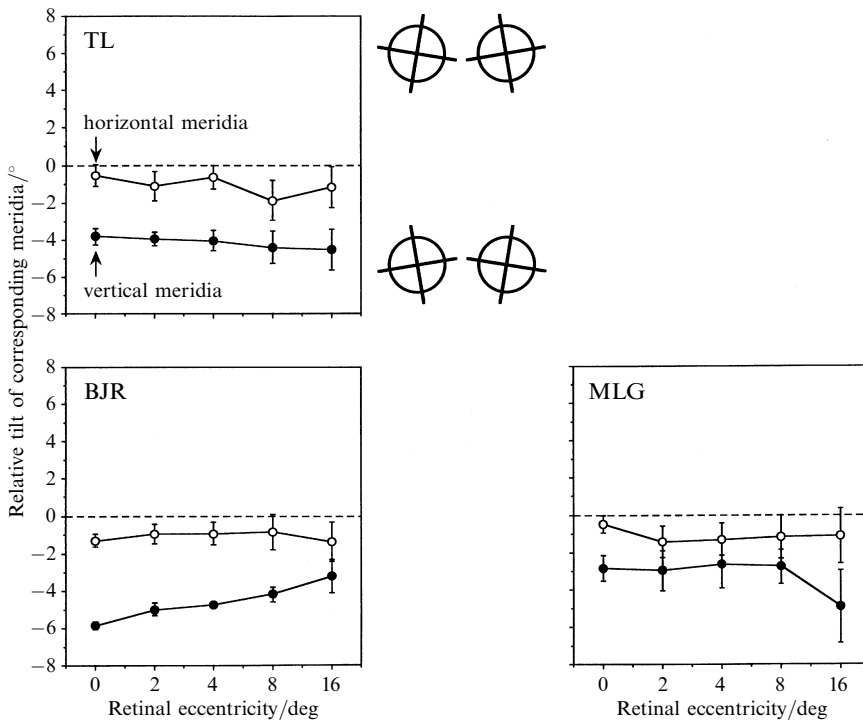


Figure 2. Graphs showing the relative tilts of corresponding horizontal meridians (unfilled circles) and corresponding vertical meridians (filled circles) as a function of retinal eccentricity for three observers. Viewing distance was 57 cm (vergence angle was 390 min of arc). Positive values on the ordinate indicate intorsion of corresponding meridians and negative values indicate extorsion of corresponding meridians, as shown by the icons to the right of observer TL's graph. A value of zero (shown by the dashed horizontal line) indicates that corresponding meridians are parallel (ie either both horizontal or both vertical). Each data point was based on the mean of a minimum of six settings and the vertical lines above and below each data point (where visible) represent ± 1 standard deviation.

⁽²⁾ It should be noted that the relative tilt of the dots, θ , measured with respect to their positions on planar projection screens, differs slightly from the actual relative tilt of the dots as viewed from the positions of the two eyes, particularly at eccentric retinal locations. However, this difference is very small and may be considered negligible for the range of eccentricities examined in the present experiment. For example, for vertically separated dots at a viewing distance of 57 cm and an eccentricity of 16 deg, the difference between a value of θ equal to 4° and the actual relative tilt is $\sim 0.02^\circ$.

It is clear that with zero eccentricity (0 deg) the corresponding principal vertical meridians of the two eyes were extorted (tilted outwards) with respect to each other for all three observers. Although some variability in the magnitude of this meridional extorsion is evident between observers, the average relative tilt of the two principal vertical meridians was -4.2° . The corresponding principal horizontal meridians were generally aligned, but exhibited a modest relative tilt that varied between -0.5° and -1.3° .

In eccentric retinal locations the corresponding vertical meridians remained offset from each other by around -4 deg even when they were located 16 deg away from the fovea. It is apparent that the corresponding horizontal meridians remained approximately aligned even when they were elevated by up to 16 deg.

3.2 The effects of vergence angle (viewing distance)

Figure 3 shows the relative tilts of the corresponding principal meridians as a function of vergence angle for the same three observers. It is evident that corresponding meridians were largely unaffected when vergence angle was varied from 780 to 0 min of arc. That is, the principal vertical meridians of the two eyes were tilted consistently outwards in opposite directions by about $\pm 2^\circ$ from the vertical and the principal horizontal meridians remained close to horizontal despite a very large change in viewing distance (28 cm to infinity). It can also be seen that reducing the dot separation from 42 deg to 21 deg under these conditions did not affect the basic pattern of the results (data shown for observer TL).

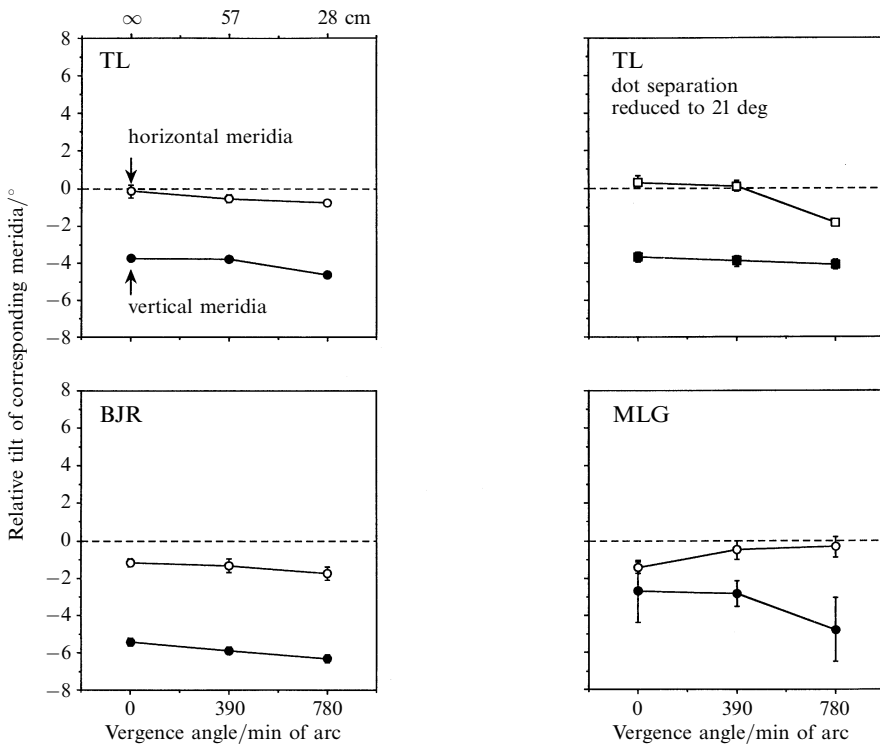


Figure 3. Graphs showing the relative tilts of the corresponding principal horizontal meridians (unfilled symbols) and the corresponding principal vertical meridians (filled symbols) as a function of vergence angle (viewing distance) for three observers. The dot separation was either 42 deg (circles) or 21 deg (squares). Positive values on the ordinate indicate intorsion of corresponding principal meridians and negative values indicate extorsion. A value of zero (shown by the dashed horizontal line) indicates that corresponding meridians are parallel (ie either both horizontal or both vertical). Each data point was based on the mean of a minimum of three settings and the vertical lines above and below each data point (where visible) represent ± 1 standard deviation.

4 Discussion

If one assumes that minimal interocular apparent motion is a valid indicator of binocular correspondence, the results of the present study confirm that the corresponding principal vertical meridians of the two eyes are extorted. The magnitude of this extorsion ($\pm 2^\circ$) is in close agreement with previous work in which similar measurement techniques have been used (Nakayama 1977; Nakayama et al 1977). In addition, we have shown that this phenomenon is not confined to the principal vertical meridians, as eccentric corresponding vertical meridians were found to be extorted by a similar amount. In contrast, the principal and eccentric corresponding horizontal meridians in the two eyes showed comparatively little or no misalignment, confirming previous reports (eg Rogers and Bradshaw 1996). A direct implication of these results is that the spatial pattern of binocular correspondence between the two retinae appears, at least to a first approximation, to be mapped by a horizontal shear distortion that extends to retinal locations at least as far as 16 deg away from the foveae. This is depicted schematically in figure 4 which shows

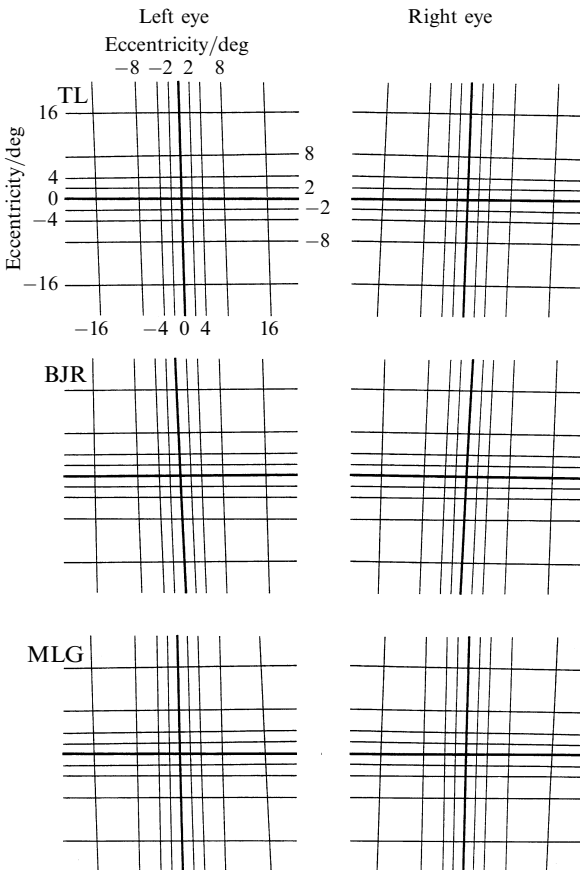


Figure 4. Schematic depiction of the absolute orientations of extended lines, on a planar surface, that would be expected to stimulate corresponding retinal meridians when the images are presented simultaneously to the left and right eyes, derived from each observer's data shown in figure 2 (the lines are based on interpolation between the positions of the dots separated by 42 deg). Lines stimulating corresponding principal meridians are shown by the thick lines that intersect at the centre of each eye's plot and those falling on corresponding meridians at eccentricities of ± 2 , ± 4 , ± 8 , and ± 16 deg are shown by the thin lines located at progressively further distances from the centre of each plot. It is apparent from the figure that corresponding vertical meridians are sheared horizontally in opposite directions in the two eyes and corresponding horizontal meridians exhibit a small degree of vertical shear.

the absolute orientations of extended lines, on a planar surface, that would be expected to stimulate empirically corresponding retinal meridians when the images are presented simultaneously to the left and right eyes, derived from each observer's data shown in figure 2 (the continuous lines are based on interpolation between the positions of the 42 deg separated dots).

As corresponding vertical meridians were clearly extorted to a much greater extent than corresponding horizontal meridians, the measured extorsion of corresponding vertical meridians cannot be due solely to the torsional states of the two eyes. Indeed, additional observations revealed that even when a larger (70 deg long), and potentially more effective, centrally positioned horizontal binocular fixation line was used to stabilise the torsional alignment of the two eyes, the measured relative tilt of the corresponding principal vertical meridians was very similar (ie $\pm 2^\circ$) to that obtained in the present study with a 3 deg fixation stimulus. This finding is important because it rules out the possibility that the observed relative tilt of the vertical meridians was due solely to torsional misalignment of the two eyes. Rogers and Howard (1991) have shown objectively that the stimulus for cyclovergence is a horizontal gradient of vertical disparities. Although the stimuli in the present study were alternated between the two eyes rather than presented simultaneously, it could be argued that any temporal vertical shear of the horizontally separated dots created as a consequence of excyclovergence of the two eyes would tend to bring the eyes into torsional alignment. This would not be the case for vertically separated dots because a horizontal shear is an ineffective stimulus for cyclovergence. Although this possibility cannot be ruled out, it seems unlikely, given that the large relative tilt of the corresponding principal vertical meridians was measured in the presence of a horizontal binocular fixation line, which would be expected to be very effective in driving stimulus-evoked cyclovergence for correcting torsional misalignment. However, a small degree of torsional misalignment may have influenced the absolute magnitudes of the tilts measured and could account for the small but consistent extorsion of the corresponding horizontal meridians that was sometimes observed (eg figure 2). Although some aspects of retinal correspondence have been shown to change with vergence angle (eg Diner and Fender 1987, 1988; Fogt and Jones 1998), introducing local distortions into the shape of the vertical-line horopter and the region of single binocular vision close to the fixation point, in the present study the relative tilt of the corresponding principal vertical meridians was found to be largely invariant with viewing distance (see figure 3). This finding is consistent with Helmholtz's assertion that the inclination of the empirical vertical horopter varies in a systematic manner with viewing distance, such that it is approximately vertical with close fixation in the horizontal plane and parallel with the ground at infinity. This in turn implies that if the eyes cycloverge with changes in horizontal vergence, the magnitude of this cyclovergence was too small in the present experiment, in which the plane of regard was the horizon plane, to affect markedly the spatial pattern of correspondence between the two eyes.

An issue that has an important bearing on the interpretation both of the present results and those of studies discussed previously (see section 1), concerns the degree to which they actually reflect the tilt of corresponding vertical meridians and, in particular, the inclination of the vertical horopter. It may be possible to ascribe at least some of these phenomena to an inhomogeneity in the sensitivity or spatial distribution of binocular mechanisms in the visual system. For example, the upper-lower hemifield anisotropy concerning the regions of best stereoscopic vision reported by Julesz et al (1976) could be taken as evidence that the sensitivities and/or numbers of disparity detectors subserving stereoscopic vision are greatest at retinal locations tilted outwards by about $\pm 2^\circ$ with respect to the vertical, perhaps because of the ecological significance of the ground plane. According to this view the detectors mediating best stereoscopic performance receive monocular inputs from the two eyes from retinal regions that lie on

extorted, but not necessarily corresponding, vertical meridians and as such the proposed inclination of the empirical vertical horopter is actually the locus of points in space which stimulate maximally sensitive binocular mechanisms, rather than points of zero binocular disparity.

Applying a similar interpretation to the results obtained with nonius lines and the minimum motion technique, which are in essence both based on the criterion of equal visual direction, is, however, much less straightforward. Indeed, one would have to make the rather tenuous assumption that inhomogeneities within the population of disparity-encoding mechanisms bias the perceived alignment or spatial positions of monocular images away from the vertical. One direct implication of this hypothesis is that figure 4 depicts the relative horizontal shear of principal and eccentric meridians with maximal binocular sensitivity rather than meridians that are necessarily in binocular correspondence. However, an alternative and parsimonious account of these phenomena is that the nonius and minimum motion methods are both valid measures of binocular correspondence and that the binocular mechanisms that respond to stimuli which fall on corresponding retinal regions are also the most sensitive (or numerous), a notion that is already implicit in some measurements of the horizontal horopter (eg Blakemore 1970; Stevenson et al 1992). Although there is at present no objective criterion against which to test this assertion, its importance in the present context lies in the fact that it emphasises the theoretical and practical difficulties that are associated with devising adequate measures of binocular correspondence and upon which the various forms of the empirical horopter are based.

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