Binocular moiré fringes and the vertical horopter

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Received 20 November 1979, in revised form 8 April 1980

Abstract. Binocular moiré fringes observed in grating stimuli are analyzed in terms of the processes of binocular fusion, the vertical horopter, and the perception of vertical.

1 Introduction
Recently David Piggins (1978) reported a phenomenon in the binocular viewing of gratings with an interocular tilt away from the vertical. When there is an orientation difference between the gratings presented to each eye, the grating appears segregated horizontally into layers at different depths (as shown in figure 1). Piggins also points out that there is also a moiré effect in which the spatial phase of the grating appears to shift at the boundaries between the layers at different depths. I shall refer to the two aspects of the phenomenon as the depth moiré and the fusion moiré respectively. These phenomena do not follow directly from the geometry of the situation. The purpose of this note is to consider the phenomena in relation to the known organization of the human stereoscopic system.

![Figure 1. Depiction of the perception of vertical counterphase gratings as a series of planes in depth. (Only one instant in time is shown.)](image)

2 Fusion moiré
The apparent phase shifts between the different layers appear to be a property of the binocular fusion system. It is well-known (Hering 1864) that the perceived visual direction of a binocular image consisting of two disparate monocular images is shifted from the monocular visual directions by the fusion system. This phenomenon is called allelotropia, and it seems to account for the phase shifts reported by Piggins.

A demonstration of allelotropia is in order since some authors maintain that fusion occurs by suppression of the image to one eye. Figure 2a depicts the case of two monocular lines bowed in opposite directions corresponding to a stereoscopic bowing in depth. When it is within the range of the fusion system, this image is seen as a single line bowed in depth but with no lateral bowing (as can be observed by free fusion of the monocular images). Thus by allelotropia the ends of the two monocular lines are perceptually shifted towards the vertical position, with a corresponding shift
in perceived visual direction. If there were suppression of one eye, the lateral bowing of the line in the other eye would tend to become visible (as can be seen by shutting each eye alternately).

When this phenomenon is applied to the case of tilted gratings, it seems that the visual system takes the disparity of each bar in one eye in relation to the closest adjacent bar in the other eye at any point in the display. The geometric situation is depicted in figure 2b. For a given angle between the monocular gratings, the operation of allelotropia would shift the perceived bars in the grating to frontal vertical, up to the horizontal level at which the two gratings are in counterphase. At this point allelotropia would tend to operate in the opposite direction, causing a perceived split in the grating. Hence the appearance of shifted layers of grating. Naturally, this process will operate only as long as the tilt falls within the range of the fusion system. Beyond this point binocular rivalry will set in and the fusion moiré will disappear.

The point of this analysis is to show that the fusion moiré is not a moiré fringe in the conventional sense of the domain of luminance additivity, but can be explained by the processes of the fusion system. The fact that the moiré disappears when the angle is too great shows that, as Kaufman (1974) pointed out, there is no luminance additivity under these conditions in the binocular summation system (although additivity and moiré fringes may occur for low-contrast stimuli). The fusion moiré described by Piggins seems to depend on an entirely different principle, that of lateral shifts in visual direction during fusion of disparate regions, or allelotropia.

![Figure 2](image-url)

Figure 2. (a) Demonstration of allelotropia. When the oppositely bowed lines of the left and right images are fused, the fused line appears vertical although bowed in depth. (b) Superposition of left-eye and right-eye views of a grating with an interocular tilt from vertical (tilt exaggerated) to show the input conditions for rotation of the bars in segments due to the different conditions of overlap. Arrows indicate direction of rotation by the operation of the fusion system.

3 Depth moiré

The existence of a series of depth planes with the same spacing as the fusion moiré follows from the geometry of figure 2b, if the monocular images are considered as producing a linearly varying binocular disparity, with shifts at the same points of crossover as in the fusion analysis. However, the quantitative prediction deviates from the measured data (Piggins 1978, figure 2). In order to explain this deviation I report some observations made over the past several years in my laboratory.

I have observed that the binocular moiré phenomenon does not require an interocular tilt. It also occurs with physically vertical gratings viewed with the eyes in primary position (except for a small amount of convergence, e.g. 1 deg).
The phenomenon is much more obvious if the grating is alternating in counterphase (e.g. at 8 Hz). With a grating of 2 cycles deg\(^{-1}\) of 10 deg in extent viewed at 1 m, most observers report that the display breaks into approximately three planes receding in depth from bottom to top in the display (see figure 1). A significant point is that the lines in each horizontal strip appear vertical in depth, with the strip above it displaced backwards but again untilted. This observation is in accord with Piggins' results, which appear to suggest a nonzero number of observed fringes at zero orientation difference (although he does not specify the direction of tilt).

Piggins attributes this mismatch with the geometrical prediction to cyclofusional eye movements, but the observation of the binocular moiré with zero tilt and the eyes in primary position would seem to invalidate this suggestion, since there should be no cyclotorsion in primary position. Instead I attribute the effect to the fact that the vertical horopter is tilted backwards. This surprising arrangement was originally suggested in the 19th century and the evidence drawn together by von Helmholtz (1866/1925; see also Tyler and Scott 1979).

Outside the horizontal visual plane the nonius horopter (which is the locus of points projecting with identical visual directions in both horizontal and vertical dimensions, i.e. having zero disparity at the cortex) is a single, straight line (except for fixation at infinity) (von Helmholtz 1866/1925). That this line is tilted in depth can be explained if the projection of the vertical meridians of the two retinæ onto the cortex occurs with a small orientation difference, so that meridians which are angled about 4\(^\circ\) apart on the two retinæ project to the same set of cortical locations (Nakayama 1977; Nakayama et al 1977). The consequence of this interocular tilt is that the vertical horopter is tilted in depth by an amount which depends on fixation distance. It runs through the fixation point and a point somewhere below the eyes and above the feet. This is illustrated by a diagram from von Helmholtz showing a condition where the horopter is tilted at 45\(^\circ\) (figure 3). In a similar manner to cyclotorsion the presence of a tilted horopter produces the percept of the series of stepped planes when the grating in each eye is physically vertical. This can account for the discrepancy between the predicted and measured number of steps reported by Piggins. Naturally, if the fixation position moves up and down, the depth moiré will move with it. This is a further prediction from the horopter analysis that is confirmed by Piggins' observations. It is not predicted from the simple geometry of crossed gratings.

The final observation that requires explanation is the fact that in physically vertical gratings each of the strips appears vertical in depth, although there is an effective tilt of 4\(^\circ\) producing the backward shift of each strip. This point has been addressed by:

![Figure 3. Diagram from von Helmholtz (1866/1925) showing the tilt of the vertical horopter resulting from the lateral tilt of the vertical corresponding points in the two eyes.](image-url)
Cogan (1979), who measured both the monocular tilt of the vertical in one eye relative to the tilt of the vertical in the other eye (dichoptic condition), and the depth tilt when viewed in a fused configuration (depth condition). In the dichoptic condition there was a physiological interocular tilt of between 1·5° and 3·2° across eight observers, with a mean of 2·2°. Under his viewing conditions this would have been expected to produce a mean depth tilt of physically vertical lines of 31°, on the basis of disparity at the cortex inferred from matching the monocular visual direction in the two eyes under dichoptic stimulation conditions. In fact, when apparent vertical was judged by the same observers, it occurred at a mean interocular tilt of 0·2° corresponding to a depth tilt of only 2·75°. Thus the observers did not take lines with zero disparity as perceptually vertical but rotated them so that the apparent vertical was close to true vertical. In this sense they compensated for more than 90% of the tilt in the retina-to-cortex projection, to obtain a perceptual result that was close to veridical.

When this mechanism is applied to the case of the depth moiré in vertical counter-phase gratings, it appears that the perceptual compensation is not so complete. Rather than producing a percept of a complete vertical grating, the large tilt of the horopter appears to force the separation of the grating into horizontal strips. Apparently, within each strip, the perceptual compensation can still operate, so that each strip is seen as vertical, although successive strips are displaced in depth, as described above.

4 Conclusion

The binocular moiré effects reported by Piggins reveal several aspects of the operation of the stereoscopic system. These need to be carefully considered in experiments in binocular vision, from binocular summation of gratings which may need to be aligned along the horopter, to depth perception in complex figures.

Acknowledgements. This work was supported by NIH grant R01-EY-02124, and The Smith-Kettlewell Eye Research Foundation and NIH general research grant 5501-RR-05566.

References

Hering E, 1864 Beiträge zur Physiologie (Leipzig: W Engelma)
Piggins D, 1978 “Moirés maintained internally by binocular vision” Perception 7 679-681