Rigaudiere (1975)

This is a translation of Rigaudiere (1975) by Robert P. O'Shea. I translated it in 1976 while at Department of Psychology, University of Queensland, St. Lucia 4067, Australia. That copy is lodged with the British Library, Lending Division. I revised this version of the translation slightly, added footnotes, Acknowledgements, and figure captions, and placed it on the web on 4 Jun 2003.

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FUSION AND DEPTH FROM SPATIAL FREQUENCY DIFFERENCES BETWEEN VERTICAL AND HORIZONTAL GRATINGS[1]

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INTRODUCTION

Hypotheses on the mechanisms of stereopsis

Research on the mechanisms underlying stereopsis has given rise to a number of experiments. It is not possible to investigate man directly and thus electrophysiological investigation of animals must be used to establish hypotheses concerning depth perception.

It seems for the cat and monkey that the basis of depth perception involves populations of binocular cells maximally excited by a particular horizontal disparity (Barlow, Blakemore & Pettigrew, 1967; Nikara, Bishop & Pettigrew, 1968; Hubel & Wiesel, 1970).

It would be interesting to uncover a similar process in man. However there is a problem confronting such a mechanism for central vision. Here, cortical representations of objects in front or behind fixation are separated in the two hemispheres. Despite this, objects are correctly localized up to a certain disparity limit (Ogle, 1952a, b, 1953; Westheimer & Tanzman, 1956). How then could stereoscopic vision result from the excitation of binocular cells? Blakemore (1969) suggests that an interhemispheric connection via the corpus callosum permits central binocularity and this has been verified in two cases (Blakemore, 1970a; Mitchell & Blakemore, 1970).

Studies on the precision of depth localization of stimuli with different line lengths or orientations to the two eyes (Mitchell & O'Hagan. 1972), and of the aftereffects of adaptation by a particular disparity (Mitchell & Baker, 1973) attest to the reality of such neurones.

An objective confirmation of their existence also lies in the fact that their stimulation is detectable by evoked potential techniques (Regan & Spekreijse, 1970).

These experiments allow the existence of binocular neurones activated at a distal level, and whose response seems narrowly linked to the value of retinal disparity. Such results may be interpreted by the classical theory of stereopsis -- that of geometrical disparity differences between the two eyes.

Stereopsis and spatial frequency

However, it may be argued in the light of recent experiments, that retinal disparity may not be the only cue to perception of the third dimension.

Blakemore and Campbell (1969a, b) have established the existence of neurones capable of responding to a narrow band of spatial frequencies.

The doubts cast on the specificity of spatial frequency adaptation by Nachmias, Sansbury, Vassiliev and Weber (1973) may be removed by the results of Abadi and Kulikowski (1973) and of Stecher, Sigel and Lange (1973).

Spatial frequency has been found to be sufficient to evoke recordable potential changes (Blakemore & Campbell, 1969b; Campbell & Maffei, 1970). The sensitivity of these neurones to orientation and spatial frequency is comparable not only in central vision (Campbell & Kulikowski, 1966; Gilinski, 1968; Blakemore & Campbell, 1969a; Kulikowski, Abadi & King-Smith, 1973) but also in peripheral vision (Sharpe & Tolhurst, 1973). Measures of visually evoked potentials when orientation is tested (Maffei & Campbell, 1970; May, Leftwich & Aptaker, 1974) lend support to the psychophysical results. Blakemore and Sutton (1969), Blakemore, Nachmias and Sutton (1970), and Blakemore and Nachmias (1971) have studied the adapting effects of a given spatial frequency and orientation. The existence of these aftereffects has been observed (Blakemore, Mauncey & Ridley, 1971, 1973), and their persistence, and the fact that they partially transfer interocularly have been noted (Gilinski & Doherty, 1969; Blakemore et al., 1970; Sharpe, 1974).

Two modes of analysis by the visual system of the form of objects may be proposed: (i) A Fourier analysis of the retinal image into component spatial frequencies. This information will be transmitted to the brain by broad-band channels and, (ii) A subsequent synthesis of this information in the cortex for reconstruction of the form of the object (Maffei & Fiorentini, 1972).

The perception of the third dimension may follow a similar process, with a retinal spatial frequency comparison, then recognition of the depth by activation of appropriate neurones. Blakemore (1970b), then Fiorentini and Maffei (1971) showed that, in certain circumstances, binocular depth perception may be interpreted in terms of the monocular spatial frequencies.

This hypothesis may be demonstrated by the binocular inspection of two images of slightly different spatial frequencies. In effect, when two different spatial frequency gratings are physically superimposed a new image is produced of "spatial beats", with a frequency equal to the absolute value of the difference between the two component frequencies. Such beats are seen only when the two gratings are seen by the same eye, they are never seen with dichoptic viewing. If two vertical gratings are presented one to each eye, a fused grating is seen in the frontal plane. If the frequency of one is slightly larger than the other, the binocular grating seems tilted around the vertical axis with the edge closer to the subject determined by the larger frequency.

The effect is global, the binocular image is really fused in one plane; it is observed across a limited range of frequencies (0.5 to 15 c/deg). The plane of subjective rotation increases as a function of the relationship between the left and right frequencies, then disappears. Beyond a certain frequency difference called the "fusion break", global fusion is lost and rivalry between the two gratings takes place.

Binocular presentation of vertical gratings with a spatial frequency difference produces a related visually evoked potential (Fiorentini & Maffei, 1970). This striking correlation between depth perception accompanying binocular presentation and cerebral electrical activity strongly suggests the presence of binocular cortical neurones.

These experiments lead to the possibility of stereopsis reflecting the activity of binocular neurones at a superior level, based on spatial-frequency analysis.

Within the framework of our research into the mechanisms underlying stereopsis, we became very interested in delving more deeply and completely into this depth effect which results from the fusion of two different spatial frequencies.

EXPERIMENT

We measured the effect of fusion of two vertical gratings of the same or different frequencies by a different method to that of Blakemore (1970b) and Fiorentini and Maffei (1971). We related the extent of fused rotation to the ratio of the number of cycles seen by the left and right eyes for a range from 0.5 to 12 c/deg.

It was of interest to see if fusion of horizontal gratings were possible over the same range of frequencies. Blakemore (1970b) found in this case no effect. We find, for our experimental conditions, that two horizontal gratings give rise to an apparent rotation as a function of the ratio between left and right frequencies.

We make speculations on the relationship of the extent of rotation to spatial frequency. Finally, our discussion focuses on the various models of stereoscopic analysis.

Experimental apparatus (Fig. 1)

We used a haploscope which permitted presentation of various gratings to each eye.

On each arm of the haploscope was placed a grating slide (m-m') of various frequencies, back illuminated so its image was focused on a screen seen through an aperture of 3 deg. (E-E~). The two images were carefully aligned (M-M') and were fused by means of two half-silvered prisms in the centre of the apparatus and in the medial plane of the observer. The fusional plane (Fig. la) was dark (5.3 nits) and moveable along a graduated axis from which its position could be read.

The objective plane was indicated by the fusion of the left and right apertures.

Gratings used

The test gratings are peaked, of strong contrast and with an average luminance of 6.5 nits. For each measurement series, a reference spatial frequency was chosen: 0.5 c/deg - 2.8 c/deg - 4.0 c/deg - 5.8 c/deg - 10.8 c/deg - 11.7 c/deg.

The difference between the left and right test gratings may be expressed as a ratio of the number of cycles. This ratio may be represented as a positive percentage (R/L - 1) or as a negative percentage (1 - R/L).

Procedure

For each reference frequency, extent of rotation of the fused image was measured in both directions for horizontal and for vertical orientations.

Initially, the gratings were objectively equal, then the chosen differences were introduced. Thanks to the moveable reference plane P, the perceived depth of the left and right extremities of the fused image could be determined. Observations ceased when objective fusion was lost.

Analysis of results

For each frequency and ratio of cycles, the mean and range of 15 depth judgements were computed for left and right; this permitted a calculation of the apparent rotation of the fused image in reference to an actual plane, and the maximum error. By convention, this rotation will be positive (in the trigonometric sense) if the right side is closer to the observer than the left, and negative for vice versa.

RESULTS

The results of these experiments allow the tracking for one subject (FR) of the *changes in rotation of the fused image* as a function of the relationship of cycles for right and left images expressed as a percentage for *horizontal and vertical gratings*. We present these graphs for each of the reference frequencies: 0.5 c/deg (Fig. 2) - 2.8 c/deg (Fig. 3) - 4.0 c/deg (Fig. 4) - 5.8 c/deg (Fig. 5) - 10.8 c/deg (Fig. 6) - 11.7 c/deg (Fig. 7). At each percentage of R/L cycles on the abscissa we show, on the ordinate, the corresponding value of perceived rotation in degrees with the standard error.

Vertical gratings

Figure 8 shows the six traces of perceived rotation of the fused grating (vertical) to facilitate comparison and to allow the recognition of general trends and individual differences.

We find that the rotation of the fused grating decreases regularly as the ratio R/L decreases. For large percentage differences, a flattening out of rotation is evident (at 2.8, 4.0 & 11.7 c/deg) and elsewhere a decrement in rotation (for 0.5 c/deg and for 10.8 c/deg).

The maximum rotation is not at the same percentage value for positive and negative directions. Four c/deg shows this most clearly.

Fusion was lost at ratios of the order of plus or minus 30 percent; this corresponds well with the maximum values found by Blakemore (1970b).

For two objectively identical gratings (R/L = 0%), the apparent rotation is not zero, and varies, depending on frequency, between 1 and 5 degrees. This is maximal for 11.7 c/deg and minimal for 4 c/deg. This rotation is perhaps due to optical aniseikonia on the part of the observer.

The rotation of the fused image is zero between R/L ratios of -0.5 and 1 percent. The measurement of the vertical aniseikonic component by the classic test (Spatial Image Measurement of the American Optical Company) gives a ratio of -1.25 percent.

Horizontal gratings

The direction of perceived rotation of the horizontal fused image is much different from that observed for vertical orientations; the extent of rotation is less across a range of positive and negative ratios. One point we feel is most important to stress concerning the direction of rotation of the horizontal fused image: it is opposite to that of the vertical image.

Figure 9 combines the six graphs of rotation plotted for each frequency. This figure highlights the nature of the rotation.

The traces are clearly separated, much more so than for the vertical gratings. The characteristic change is a flattening out of rotation at large frequency ratios; this is particularly marked for 10.8 c/deg. Blakemore (1970b) found no rotation with horizontal gratings. It is possible that he tested this with a frequency difference where the rotation is very weak and difficult to discern. In effect, for our experimental conditions, rotation for frequencies of 10.8 and 11.7 c/deg is weak and constant for a large range of negative ratios.

The ratios at which fusion breaks vary from one frequency to another: -- positive and negative ratios yield different values for the same frequency -- they clearly differentiate themselves from those observed for vertical gratings for two frequencies (10.8 & 11.7 c/deg); in both cases fusion changes little with R/L ratio, and is maintained for quite large R/L ratios.

For two objectively identical gratings, apparent rotation of the fused image is large: between -10 degrees for 0.5 c/deg and -22 degrees for 5.8 c/deg. This rotation is perhaps an artifact of the horizontal component of aniseikonia of the observer; the measure by the standard test gives a R/L ratio of -1 per cent.

The point at which the fused image was seen as frontoparallel lies at large R/L ratios between -6 percent (for 0.5 c/deg) and -20 per cent (2.8 c/deg). It should be noted that these values are particularly high, if disparities produced by aniseikonia are compared.

INTERPRETATION AND DISCUSSION--

ANALYSIS IN TERMS OF SPATIAL FREQUENCY AND ANISEIKONIA

Vertical gratings -- geometric effects

The depth effect observed from the fusion of two vertical gratings with different spatial frequencies resembles that obtained in the case of aniseikonia: a disparity introduced to retinal images in a horizontal meridian leads to the apparent rotation of the frontal plane about the vertical axis, called the "geometrical effect" (Ogle, 1950, 1955, 1962; Bourdy, 1956, 1960, 1961, 1963, 1967, 1972; Bourdy & Paille, 1972).

One could claim that the effect under examination results from no more than the linear disparity between homologous image points rather than from a spatial frequency analysis as suggested by Blakemore (1970b).

To this end we have plotted the rotation of the vertical fused gratings as a function of spatial frequency for a large range of positive and negative R/L ratios (Fig. 10).

For all these ratios, we find a relationship between rotation and spatial frequency. These results clearly show the influence of spatial frequency on the rotation of vertical gratings.

Horizontal gratings -- induced effect

Rotation of fused horizontal gratings is the reverse of that found for vertical gratings. It resembles, because of the changed direction, the apparent rotation of the frontal plane produced by a vertical disparity between retinal images, named the "induced effect" by Ogle.

It could be asked, in the light of this similarity, if the depth produced by fused horizontal gratings of different spatial frequencies is not a form of the induced effect, and if there is not yet complete explanation of the mechanism of the induced effect, may not it underlie the effect found here.

To examine this, we plot the rotation of horizontal gratings as a function of the spatial frequency for the full range of R/L ratios (Fig. 11).

We find, for all ratios, a clear dependence of the extent of rotation on spatial frequency.

Thus, for our experimental conditions, the graphs for horizontal and vertical gratings demonstrate the existence of a depth effect related to spatial frequency. It seems that the depth produced by fusion of two gratings of different spatial frequency may not be explained only by disparity or only by pure aniseikonia. One must not then consider, as Shipley and Hyson (1972) hold, that we are in the presence of a particular example of aniseikonia. The use of spatial frequency differences appears on the contrary to be a better means for understanding the induced effect, for doing a different analysis of it, and for approaching the processes underlying binocular interaction.

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Footnotes

1. Actual address: Hôpital Lariboisière, Centre de Biophysique Sensorielle, 2 rue Ambroise Paré, 75010, Paris, France.

2. This study forms part of a thesis for the degree of Doctor submitted to the University of Paris VI on 13 March 1973. It also forms the basis of a communication in collaboration with C. Bourdy at the meeting of the French Society of Physiological Optics on 15 March 1973.

Figure captions

Fig. 1. Diagram of the haploscope and the observer's field of view. (a) Reference plane. (b) Rotation of a fused grating.

Fig 2. Variation of the rotation of a fused grating as a function of the R/L□percentage ratio for a reference grating of 0.5 c/deg. [dashed line, vertical grating; solid line, horizontal grating; subject FR]

Fig 3. Variation of the rotation of a fused grating as a function of the R/L□percentage ratio for a reference grating of 2.8 c/deg. [dashed line, vertical grating; solid line, horizontal grating; subject FR]

Fig 4. Variation of the rotation of a fused grating as a function of the R/L□percentage ratio for a reference grating of 4.0 c/deg. [dashed line, vertical grating; solid line, horizontal grating; subject FR]

Fig 5. Variation of the rotation of a fused grating as a function of the R/L□percentage ratio for a reference grating of 5.8 c/deg. [dashed line, vertical grating; solid line, horizontal grating; subject FR]

Fig 6. Variation of the rotation of a fused grating as a function of the R/L□percentage ratio for a reference grating of 10.8 c/deg. [dashed line, vertical grating; solid line, horizontal grating; subject FR]

Fig 7. Variation of the rotation of a fused grating as a function of the R/L□percentage ratio for a reference grating of 11.7 c/deg. [dashed line, vertical grating; solid line, horizontal grating; subject FR]

Fig 8. Comparison of the rotations of fused gratings as a function of the R/L□ percentage ratio of their number of cycles for all frequencies studied. VERTICAL GRATINGS. [subject FR]

Fig 9. Comparison of the rotations of fused gratings as a function of the R/L□ percentage ratio of their number of cycles for all frequencies studied. HORIZONTAL GRATINGS. [subject FR]

Fig 10. Variation of the rotation of a fused grating as a function of a given R/L□ percentage ratio of cycles (positive and negative percentages). VERTICAL GRATINGS.

Fig 11. Variation of the rotation of a fused grating as a function of a given R/L□ percentage ratio of cycles (positive and negative percentages). HORIZONTAL GRATINGS.