V

THE PERCEPTUAL CONFLICT IN BINOCULAR RIVALRY

W. J. M. Levelt*

Normally, the human mind makes a portrait of the visual world with the aid of both eyes. The small differences between the retinal images, due to their differences in point of view, yield the well known binocular impression of depth. With the use of instruments, the natural correspondence may easily be disturbed. In microscopy, for instance, fusion problems may arise and, if not successfully met, they can lead to the occurrence of binocular rivalry. The present study throws a light on the origin of this binocular rivalry. More detailed communication can be found in the publications 157 *and* 164 *of the cumulative bibliography.*

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More than two centuries ago, Du Tour (1760) concluded from the existence of binocular rivalry that in normal binocular vision, every point of the visual field is only perceived with one eye. He understood that by stimulating the two eyes with incongruent patterns, more knowledge in the structure of normal binocular vision could be obtained. This structural question has occupied a number of distinguished scientists ever since. Among them, Helmholtz may be mentioned. He gave a 'mental' interpretation of fusion and rivalry (Helmholtz, 1866). From each of the eyes an independent percept is produced. Therefore, there is double perception in the rivalry situation. But we are aware of only one of them, which is selected by processes of attention. There is no physiological interaction between the two sensorial processes. In fact, this view has been developed in opposition to Hering's theory (1866). Hering assumed sensorial mixture of the two excitations. The shares of the two eyes may be different in this mixture, but absolute dominance of one of the eyes is only the limiting state of mixture. Normally the excitations compete in the binocular field. The result of the competition is, among other things, determined by the presence of contours, which are always dominant. We mention these theories in order to suggest the occurrence of very divergent possibilities for a structural theory of rivalry and fusion. Arguments pro and con are given elsewhere (Levelt, 1965). Suffice it to say that the present author is much inclined towards the views of Hering.

In this century, much of the work on binocular rivalry has been done without reference to the structural problem. Starting with Breese

(1899, 1909), most authors have studied the effect of all kinds of stimulus variables on the binocular alternation process in rivalry. Actually, they have mainly been interested in dominance times and alternation frequencies, generally without questioning why such a perceptual conflict should arise. However, any fertile treatment of the alternation problem is only feasible on the basis of proper evaluation of the visual conflict which is apparent in the rivalry situation. In this paper some of the experiments are described which have enabled the conclusion that a perceptual conflict should arise in the complex binocular situation, when binocular proximity of non-corresponding contours occurs. This conflict is traced down to the incompatibility of two simple mechanisms of binocular interaction. One is called 'binocular brightness averaging' according to the law of complementary shares, and the other is the 'contour mechanism'.

Binocular brightness averaging

If the eyes are presented with identical fields of equal luminance (E_b), and the luminance of the left field is increased (up to E_l), one may keep the apparent binocular brightness constant by simultaneously decreasing the luminance of the right field (to, say E_r). In this way one can measure an equibrightness curve, i.e. the locus of luminance pairs, producing the same binocular brightness.

a. Equibrightness curves

Procedure. Equibrightness curves were measured by alternatingly presenting an observer with a binocular comparison field and a binocular test field. The comparison field provided the observer with a brightness standard. It is shown in Fig. 1. For the comparison field

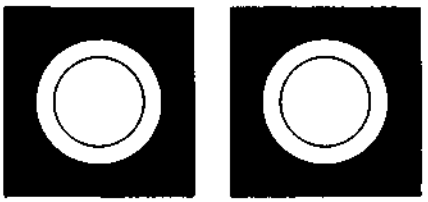

Fig. 1. Stimuli used to determine equibrightness curves. The discs subtend 3° of visual angle. The left and the right test and comparison fields contained a concentric circle, 2° in diameter, with outline diameter of 3′, in this first experiment.

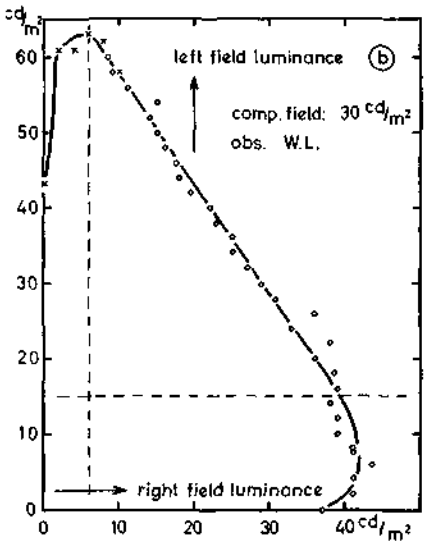

Fig. 2. Equibrightness curve (observer W.L.)
Comparison field luminance: 30 cd/m².
o Observer adjusts the luminance of the right test field
x Observer adjusts the luminance of the left test field.

the luminances of the monocular fields are equal and constant. They are foveally presented in an experimental stereoscope. The observer looks through artificial 1 mm pupils. By pushing a button the observer replaces the pair of comparison fields by a pair of test fields. They are presented to the same parts of the retinas and are geometrically equal to the comparison fields. However, the luminance of one of the test fields is set by the experimenter, whereas the luminance of the other test field has to be adjusted by the observer by changing the lamp current, so that the binocular brightness – produced by the pair of test fields – is equal to the brightness of the pair of comparison fields. The observer can alternate test and comparison fields at will, until he is satisfied with his adjustment.

Results. One of the equibrightness curves thus measured is presented in Fig. 2. The comparison fields had been fixed at a luminance of 30 cd/m² for this series of measurements. The general trend of this curve (and of the others) appears to be as follows: For test field luminances higher than a particular value – indicated by dotted lines in the figure – the function is linear. It can be expressed as $w_l E_l + w_r E_r = C$. The slope of this curve is different for different subjects; w_l and w_r can

be interpreted as weighting coefficients, which reflect eye dominance. The observer in this experiment was strongly right-dominant apparently. The fact that the curves are linear (if we disregard their tails for the moment) implies that binocular brightness can simply be described in terms of averaged monocular luminances, and that thus far there is no reason to claim that it is a matter of averaging of 'sensations'. The latter claim was made by Sherrington (1908). He went so far as to speculate that the sensorium of the right eye is completely separated from that of the left eye. Whatever may be the truth in this Helmholtzian view, our curves suggest that the binocular brightness impression does not result from simple averaging of monocular sensations. For it is known from psychophysical studies that monocular, as well as normal binocular, subjective brightness is a non-linear function of stimulus intensity. Irrespective of whether this is a logarithmic function (Fechner) or a power function (Stevens), or any other non-linear function, if sensations were merely averaged, an equibrightness curve could not show a linear relation between monocular luminances, as it does in our result. Therefore, if binocular brightness is a matter of combining sensations, the results suggest that they would have to be combined in a more complicated manner, in such a way, in fact, that the resulting binocular brightness is the same as if luminances were averaged.

b. The law of complementary shares

The putative mechanisms in binocular rivalry can now be specified by assessing the effect of a monocular contour on the binocular brightness impression. For this, an experiment was performed which is a natural extension of the one described above.

Procedure. The experiment is the same in all respects except one. Whereas in the former experiment a circle was present in both test fields, in the present experiment a circle is introduced in only one of them, i.e. it is a monocular contour now. This was also the case for the comparison fields, but we could show that elimination of a contour from one of the comparison fields did not affect their apparent binocular brightness, i.e. the experimental standard.

Results. Fig. 3 shows a pair of curves thus obtained. Fig. 3a is the equibrightness curve for the monocular circle in the left field, Fig. 3b the one for a circle in the right field only. The curves are linear again, except for the tails. The linear part of each of these curves may again be described by $w_l E_l + w_r E_r = C$. The apparent brightness is per

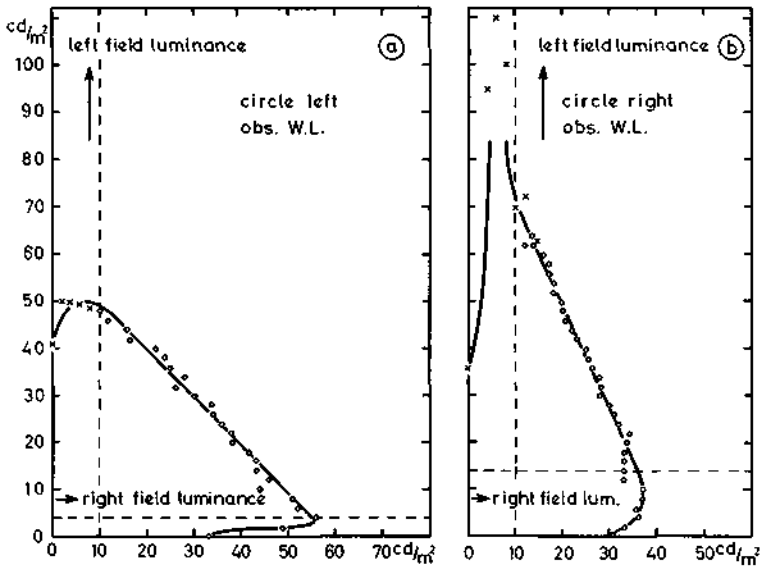

Fig. 3a, b. Equibrightness curves with monocular contour information (observer W.L.). Circles in left and right field, respectively. Comparison field luminance 30 cd/m².

definition the same for the curves of Figs. 2 and 3 (the same standard was used). For this observer, but also for all others, we find that the three curves coincide in the point $E_l = E_r = E$. As the brightness impression is equal for these three situations we have $(w_{l,1} + w_{r,1})\ E = (w_{l,2} + w_{r,2})\ E = (w_{l,3} + w_{r,3})\ E$. Stated otherwise: the sum of the weighting coefficients is the same for these points, and hence is a constant for the three curves. But the ratio of the weighting coefficients is different in the three situations. This may be called *the law of complementary shares*. It simply states that, if the weighting coefficient for the field in one eye is increased, the weighting coefficient for the corresponding field in the other eye is decreased in the same measure. It is convenient to define a share as a proportional contribution, i.e. with values between 0 and 1. We know that the sum of w_l and w_r is constant. This constant is indefinite, therefore we may put $w_l + w_r = 1$, without loss of generality; w_l and w_r are proportional shares, then. Thus, under this particular definition of 'share', the law of complementary shares is expressed by $w_l + w_r = 1$.

The shift in weighting coefficients in the just described experiment is induced by the mere presence of a contour. If a circle is presented in the left field only, w_l is increased at the expense of w_r, and *vice versa* for the situation in which a circle is given in the right field only. The weighting coefficients are constant, however, if the contour information does not change. This may be called *the rule of constancy*. But w is not an all-or-none function of the presence of a contour. For the fixation point, w appears to increase when the angular distance between the fixation point and the monocular contour is made smaller and smaller for the eye concerned. To get an impression of the maximum w-value for an eye, and thus for the minimum w for the contralateral eye, the following experiment was performed.

a. Amplitude of the variation in weighting coefficient

Procedure. The stimulus conditions for this experiment are shown in Fig. 4. The right test field is a square of 14° × 14°. Its luminance is fixed at 100 cd/m². The right comparison field is identical, but its luminance is adjustable by the observer. The left test field consists of two parts: a central disc of variable size, with luminance fixed at 12 cd/m², and a surrounding field (14° × 14°) at luminance 3.6 cd/m². The left comparison field has the same pattern; the luminance of the central disc is always the same as that adjusted by the observer for

Fig. 4. Stimuli used to determine w_l as a function of field size.

the right field, the luminance of the surrounding area is always 30% of that of the central disc. The observer had to adjust the pair of comparison fields, until the brightness of the central disc appeared equal for both test field and comparison field. The observer was requested to fixate the centre of the disc. Experimental variable was the size of the disc; the four values are 7°, 5°, 3°, and 1° of visual angle. The conditions were presented in an order according to a latin square design. Two groups of four observers took part in the experiment.

TABLE I. w_l-values of eight observers at different disc sizes.

Size	1°	3°	5°	7°
Observer				
1	.84	.79	.74	.80
2	.96	.87	.95	.88
3	1.00	.98	.97	.97
4	.91	.83	.77	.79
5	.94	.91	.82	.80
6	.99	.90	.88	.86
7	.82	.81	.79	.77
8	1.00	1.00	.94	.94
Mean	.93	.89	.86	.85

Results. Individual values of w_l have been calculated for the four disc sizes. The results are given in Table I. An analysis of variance shows that w_l increases with decreasing diameter of the discs (the regression is significant at the 0.001-level). In Table I it is seen that at 1° for observers 3, 6, and 8, w_l approaches the unit value as closely as adjustment errors permit. In view, moreover, of the increasing trend in the mean w-values with decreasing size of the disc, the data strongly suggest that in the immediate neighbourhood of a monocularly presented contour, binocular brightness impression is exclusively determined by the luminance of this monocular field. This may be called the *contour mechanism*. Where the distance d between fixation point and contour is decreased, the w for this monocular area is increased to a maximum of unity: $w \to 1$, if $d \to 0$.

The law of complementary shares, the rule of constancy and the definition of shares as proportional contributions provide us with an easy means to determine what an observer sees, if we know that his shares are w_l and w_r and that the respective luminances of the two fields are E_r and E_l, because his brightness impression is the same as that when he looks with both eyes at a field with luminance $E_b = w_l E_l + w_r E_r$. For, the so defined pair of monocular fields (E_b,E_b) is on the same equibrightness curve as pair (E_l,E_r), because $w_l E_b + w_r E_b = (w_l + w_r)E_b = (w_l + w_r).\ (w_l E_l + w_r E_r) = w_l E_l + w_r E_r$. In the following we shall speak of the apparent brightness produced by some stimulus pair (E_l,E_r) in terms of E_b . E_b is not the psychological quantity of apparent brightness, then, but it is the luminance of a

field observed with both eyes, which produces the same apparent brightness as (E_l,E_r). We know that the apparent brightness is a monotonically increasing function of E_b, but the nature of this function is irrelevant to our further discussion.

b. 'Tails' of the equibrightness curves

So far we have not considered the non-linear 'tails' of the equibrightness curves. In terms of the constancy rule for weighting coefficients, we should say that this rule is not valid for the extreme parts of the curve, i.e. if one of the test field luminances is low. But in fact, this behaviour can also be attributed to the contour mechanism. For it is clear that if the luminance of one test field, say the left one, is below threshold, contour information is present in the right field only. Therefore, for these low values of E_l, w_r will increase at the expense of w_l. In order to match with (E_b,E_b), it should be true that $w_rE_r + w_lE_l = E_b = 30\ cd/m^2$. If $E_l = 0$ and $w_r = 1$, this means that $E_r = E_b = 30\ cd/m^2$, and so the curve has to turn back to $E_r = 30\ cd/m^2$, for $E_l = 0$. But for fields of the size used in these experiments (3°), we may expect that $w_r < 1$, and therefore that $E_r > 30\ cd/m^2$ in these situations. This is clearly the case. It should be remarked that Fechner's paradox – the increase in brightness impression when the weakest stimulated eye is closed – can be explained in the same way.

c. A brightness paradox

Rather paradoxical stimulus situations can be constructed on the basis of knowledge of the law of complementary shares and the contour mechanism. An example is given in Fig. 5.
Consider Fig. 5 and compare discs A and C. For the centre of these discs the stimulations of the eyes are identical, black for the left eye, white for the right eye. Will therefore the apparent brightness of A be equal to the stereoscopic brightness of C? And compare discs B and C. The stimulation is quite different for these discs, both are black in the left field, but C is white in the right eye, whereas B is black again. Does C in fact look substantially brighter than B does? These questions may be answered by applying the said rules. For the sake of simplicity, the luminance of the black discs is supposed to be zero, whereas the bright field has luminance 1.
Disc A: a contour is present in both eyes, therefore – disregarding eye dominance – we have $E_b = \frac{1}{2}.0 + \frac{1}{2}.1 = \frac{1}{2}$.

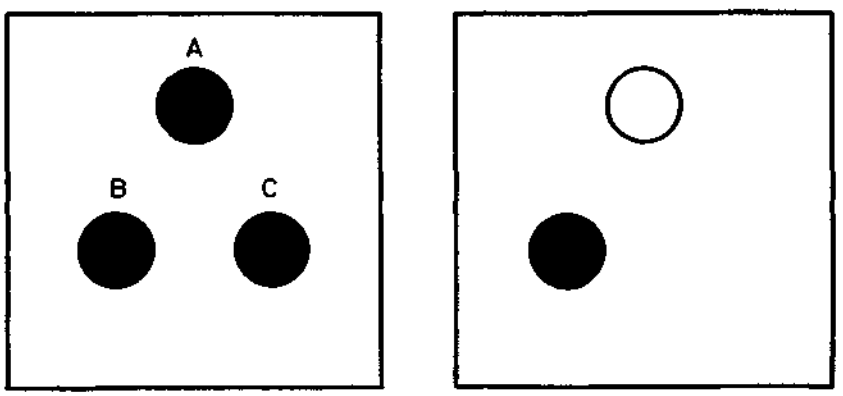

Fig. 5. Stereoscopically the disc A is considerably brighter than C, while B and C are not very different in brightness.

Disc B: corresponding contours in both eyes: $E_b = \frac{1}{2}.0 + \frac{1}{2}.0 = 0$.
Disc C: a contour is only present in the left field, hence $w_l \to 1$. For $w_l = 1$ we get $E_b = 1.0 + 0.1 = 0$, so $E_b \to 0$ in this situation, dependent on the size of the disc.
Hence both questions should be answered negatively. Disc A will look brighter than C, whereas B and C will not differ very much. The reader may verify these predictions himself by using a stereoscope to examine Fig. 5.
This type of effects can be produced at will now. Another example is shown in Fig. 6. It has been designed as an argument against the

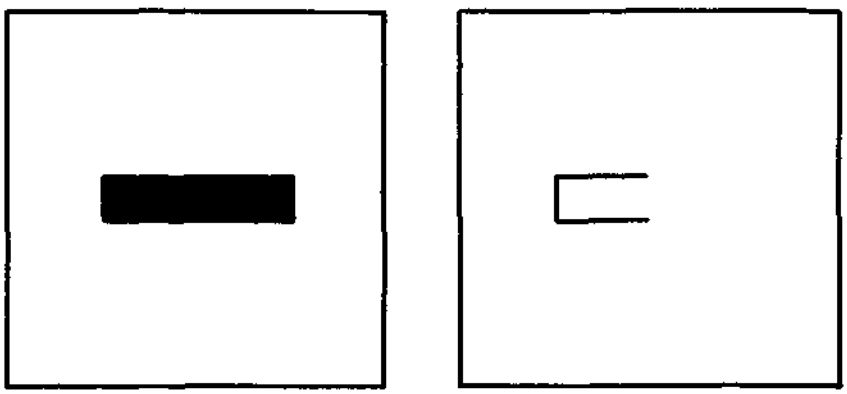

Fig. 6. An argument against the Gestalt explanation of rivalry. The Gestalt of the bar is disturbed stereoscopically. The left half appears grey, shading into black in the right half.

Gestalt-theory of binocular rivalry (Gellhorn, 1924). This theory says that a Gestalt is present or absent *in toto* in binocular rivalry, but is never disturbed.

Our theory, however, predicts distortion of the black bar in the binocular perception of Fig. 6. The left part of the figure should be similar to A in Fig. 5, whereas the right part of the bar is in the situation of C in Fig. 5. So, it is predicted that the bar looks grey in the left half, shading into black in the right half. This is also easily verified by means of a stereoscope. The bar is clearly disturbed. Binocular interaction functionally precedes Gestalt-formation.

Conflict of averaging and contour mechanism

a. Rivalry

Having established, firstly the mechanism of binocular brightness averaging according to the law of complementary shares ($w_l + w_r = 1$), and secondly the contour mechanism ($w \to 1$, if $d \to 0$), it is not difficult to show that these two mechanisms necessarily come into conflict if two non-corresponding but adjacent contours are presented to the eyes. Within a binocular area T, these contours give rise to a conflict in the partition of the weights. The contour in the left field produces a tendency for w_l to increase in area T, and the non-corresponding contour in the right eye, in its turn, will produce a tendency for an increase of w_r; in both cases on the basis of the contour mechanism. But an increase of both w_l and w_r would obviously violate the law of complementary shares: w_l and w_r would no longer add up to unity. This is the situation of binocular contour rivalry. From the interaction of two rather simple mechanisms it can thus be concluded that a perceptual conflict should arise in the complex binocular situation where there is proximity of non-corresponding contours. Apparently the conflict is resolved by the abrogation of the rule of constancy, in such a way that the first tendency – increase of w_l – triumphs over the other – increase of w_r – for some time, after which the position is reversed. The law of complementary shares is thus saved by an alternating process. The aim of this paper is only to show the source of conflict; characteristics of this alternation process are described elsewhere (Levelt, 1965).

b. Fusion

There is no reason to expect the case of corresponding contours to be different from that of non-corresponding contours. There is no strict reason to believe in a special 'fused situation', in which the weighting coefficients are suddenly $\frac{1}{2}$ for both eyes, homogeneously over the whole visual field. On the contrary, it is quite likely that in this case, too, parts of the fields will enter into rivalry. However, one will not be aware of this, as long as the stimuli are the same for the two eyes. For, if $E_l = E_r = E$, then $E_b = (w_l + w_r)\, E$ which is a constant by the law of complementary shares, even if w_l and w_r fluctuate. And for equally patterned but unequally illuminated fields rivalry will not be perceived either if sufficiently small parts of the binocular field are subject to rivalry more or less independently. This possibility is compatible with Hubel and Wiesel's findings on eye-dominance in the receptive field of the cat (Hubel and Wiesel, 1962): two cells with largely overlapping receptive fields could be of different eye dominance. This would mean that the rule of constancy is invalid for sufficiently small areas.

This 'rivalry explanation' of fusion is attractive for several reasons. One of them may be mentioned: it is possible to give such a rivalry-explanation of Panum's fusional areas. Two lines, not falling exactly on corresponding regions of the retinas, but shifted apart by some minutes of arc are nevertheless seen as one. The extent to which this is possible determines Panum's area. But under the present assumption there is no reason any more to distinguish the case of parallel non-corresponding lines from the case of e.g. crossing lines. The 'fusion' of the lines within Panum's area may be understood as the inhibition of the line presented to one eye by the line presented to the other eye. If these two cases are to be ascribed to the same mechanism, the Panum area should have the same extent as the inhibitive contralateral action of one contour with respect to another. This may be checked. Ogle's measurements on the horizontal extent of Panum's area (Ogle, 1950) give values of 6-8′ in the foveal field. This is the region within which always only one line is seen, when a binocularly disparate pair is presented. We can compare this with Kaufman's data on the extent of contralateral suppression of binocularly crossing lines. It appeared that two vertical lines in one eye, separated by an angle ϑ, produced a contralateral suppression of a horizontal line segment between them (presented to the other eye) during about 50% of the time for all angles within $\vartheta = 14'$. Half of this value is the suppressive

extension in one direction. This value of 7′ accords with Ogle's data on Panum's area.

This study may be concluded by one other remark on the rivalry-explanation of fusion. Verhoeff (1935), Asher (1953), and Hochberg (1965) likewise extrapolate the rivalry situation to the state of binocular fusion. All of them more or less explicitly use all-or-none terms to describe their assumptions: some point in the binocular field is perceived with either one or the other eye, nothing in between; in our terms: $w_l = 1$ or $w_r = 1$. However we found that intermediate situations ($1 > w > 0$) are quite normal, being dependent upon distance to contours. Moreover, Hubel and Wiesel's experiments also showed that absolute eye-dominance was exceptional in receptive fields of single cortical cells. The all-or-none thesis seems to be too simple. It is, moreover, an unnecessary assumption, if one wants to explain fusion and rivalry by the same mechanism.

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