Binocular Combination of Contrast Signals from Orthogonal Orientation Channels

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In a series of psychophysical experiments, observers compared the apparent contrast of a dichoptic stimulus (contrast edges of orthogonal orientations in the two eyes) and a monocular stimulus (a pie pattern in one eye and a blank field in the other eye). When the contrast of the dichoptic stimulus was low (2–3%) the two orthogonal edges were perceived as a stable pie pattern and its apparent contrast matched with that of a monocular pie pattern whose contrast was twice the contrast of the dichoptic stimulus. The dichoptic contrast gain (monocular/dichoptic contrast ratio) decreased with increasing dichoptic contrast. Although the observers showed an inability to discriminate the apparent contrasts of the dichoptic and the monocular pie patterns, they were able to tell which stimulus was the dichoptic one in a forced choice paradigm. A binocular contrast preservation model was proposed for binocular combination of contrast signals from orthogonal orientation channels.

Binocular summation   Binocular rivalry   Contrast

INTRODUCTION

Binocular summation is a subtle effect that is not as salient as stereoscopic depth perception or as striking as binocular rivalry. However, because binocular summation is closely related to a fundamental question of binocular vision, namely, are there any binocular interactions between the two eyes, it has been the subject of some very creative studies. Early causal observations usually led to the conclusion that monocular performance was just as good as binocular performance, in terms of perceived brightness, contrast or visual acuity. The world appears just the same when one closes one eye. The proponents of the suppression theory of binocular vision, such as Verhoeff (1935), used this kind of observation as a proof that we actually saw through only one eye at a time. However, careful measurements under controlled conditions have revealed that binocular performance is indeed better than monocular performance on various visual tasks and this binocular superiority is due to genuine neural interaction between the two eyes. The probability advantage of using the two eyes at the same time (probability summation) cannot account for the enhancement of performance during binocular viewing. Comprehensive reviews of the literature related to binocular summation can be found in two articles by Blake and Fox (Blake & Fox, 1973; Blake, Sloane & Fox, 1981).

One group of the binocular summation studies was concerned with the suprathreshold contrast perception

under binocular and monocular conditions. In one of her experiments, Birch (1979) instructed her observers to match the apparent contrast of a binocular stimulus with that of a dichoptic stimulus. The dichoptic stimulus was composed of two vertical gratings that were identical in every aspect except their contrasts. The binocular stimulus was a single grating seen by both eyes. The contrast of one of the gratings of the dichoptic stimulus (C_L or C_R) was set equal to or less than the contrast of the binocular stimulus (C_B). The observer could adjust the contrast of the other grating so that the perceived contrast of the dichoptic stimulus was equal to that of the binocular stimulus. For each C_B a dozen of contrast matches were determined at various C_Ls and C_Rs. The contrast settings thus obtained formed a "equi-contrast function". Birch (1979) found that all the equi-contrast functions could be described by a "vector summation" model

$$C_L^2 + C_R^2 + 2C_L C_R \cos\alpha = C_B^2.$$

For gratings of moderate spatial frequencies (5 and 1 c/deg), the free parameter α in the model equaled to 90 deg and the vector summation became quadratic summation. Particularly for a given C_B, contrast matching occurred when both C_L and C_R equaled to $C_B/\sqrt{2}$. Legge and Rubin (1981) showed that contrast matching data obtained with gratings of 8 c/deg could be described by quadratic summation. For gratings of very low spatial frequency (0.25 c/deg), Birch (1979) found that the vector summation model still held but the parameter $\alpha = 0$ deg and C_B became the simple summation of C_L and C_R. Therefore when fusible stimuli were presented

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to the two eyes, there is a significant amount of binocular summation.

The results described above were obtained under conditions where the gratings in the two eyes had the same orientation, the same spatial frequency and the relative phase between the two gratings was zero. They were perfectly matched and there was no binocular rivalry. This is supposed to be the optimal condition to demonstrate any binocular facilitation, because gross differences between the stimuli usually lead to binocular suppression and rivalry. Birch (1979) studied the apparent contrast of a pair of dichoptic gratings that were 180 deg out-of-phase. When the spatial frequency of the gratings was low (0.25 or 1.0 c/deg) her observers could manage to maintain binocular fixation with the aid of some binocular targets. The equi-contrast functions obtained under this condition could be described by the same vector summation model, but the free parameter α in the model had to be >90 deg (120 deg was the best fit). The relationship between binocular contrast and monocular contrast became $C_L^2 + C_R^2 - C_L C_R = C_B^2$. Because C_B always fell between C_R and C_L, contrast averaging occurred between the two eyes under this condition. Especially, if the two gratings had the same contrast ($C_L = C_R$), then the binocularly perceived contrast C_B was equal to either eye's contrast (C_L or C_R). In other words, there was no binocular contrast summation. Birch (1979) did not mention whether her observers experienced binocular rivalry. However, because the contrasts of the binocular stimulus were 20% and 30%, binocular rivalry should have been obvious.

Gratings of orthogonal orientations are usually used to demonstrate binocular rivalry. Blake (1977) showed that a grating with a contrast just above the detection threshold could suppress a grating in the other eye that had an orthogonal orientation and a much higher contrast. In a recent study (Liu, Tyler, Schor & Lunn, 1990; Liu, Tyler & Schor, 1992) we reported that when the contrasts of both gratings were low, the binocular rivalry between orthogonal gratings became unnoticeable and a stable plaid pattern was seen. Several interesting questions emerged from this observation. Can the dichoptic plaid be discriminated from a binocular plaid or a monocular plaid? How does the apparent contrast of this dichoptic plaid compare with the appearance of a monocular plaid? Blake, Yang and Westendorf (1991) attempted to answer the first question by conducting a series of psychophysical experiments in which the observers were asked to discriminate between a binocular plaid (identical plaids in the two eyes) and a dichoptic plaid (orthogonal gratings in the two eyes). They presented the stimuli at various durations and found that although binocular and dichoptic plaids were phenomenologically comparable, they were discriminable at durations longer than 80 msec. Interestingly, their observers reported seeing both stimuli as plaids but one of them appeared to be "flatter, more realistic, and/or more complete" than the other. This perceptual difference was likely to be related to a phenomenon

called binocular luster. According to von Helmholtz (1867), Dove was the first to notice that binocular combination of two surfaces with different luminosities resulted in the percept of a shimmering surface with indeterminate depth. When the stimuli were orthogonal gratings, many corresponding retinal regions would be stimulated by different luminances. Even under the conditions where binocular rivalry was not apparent, the difference in local luminance would still exist and the combined view would be lustrous. On the other hand, binocular luster would not occur in the binocular stimulus where the patterns in the two eyes were identical. Apparently in the experiments of Blake et al. discrimination was based on binocular luster because they noticed that random variation of stimulus contrast did not affect the discrimination of dichoptic and binocular plaids. In the current study we have investigated the unanswered question concerning the apparent contrast of the dichoptic plaid and the rules governing the binocular combination of contrast signals from orthogonal orientation channels.

METHODS

Stimulus

It was shown in our previous paper (Liu et al., 1992) that square-wave gratings produced more stable dichoptic plaid perception than sinusoidal gratings. To concentrate our attention to the question of the apparent contrast of the dichoptic stimulus, simple contrast edges of different orientations (as shown in Fig. 1) were used in all the experiments. In the experiments described here, the observers were asked to compare the apparent contrasts of a monocular pie pattern and a dichoptic pie pattern that were presented at the same time. The monocular pie pattern consisted of a pie pattern in one eye and a blank field in the other eye [lower stimulus pair in Fig. 1(a)]. The luminance of the blank field was the same as the mean luminance of the pie pattern in the other eye. The dichoptic pie pattern was composed of a pair of orthogonal edges presented to the two eyes [upper stimulus pair in Fig. 1(a)]. The reason to choose a monocular pie pattern as the comparison stimulus instead of a binocular one was to reduce the potential artifact of binocular luster. Binocular luster should occur in the dichoptic stimulus pair but it also occurred in the monocular pie pattern because some parts of the pie pattern were darker than the blank field in the other eye and some parts were brighter. Therefore both the dichoptic and the monocular pie patterns looked lustrous and the observer's attention could be more focused on comparing the apparent contrasts of these stimuli.

The experiments were first conducted on a system consisting of an IBM compatible microcomputer, a matched pair of TSD video monitors driven by #9 video boards[TM] and a custom contrast control circuit. Later we repeated the experiments with a Macintosh IIx computer and an RGB monitor. The edges and the pie pattern

TEST STIMULUS

DICHOPTIC STIMULUS

(a)

MONOCULAR STIMULUS

IDENTICAL STIMULUS

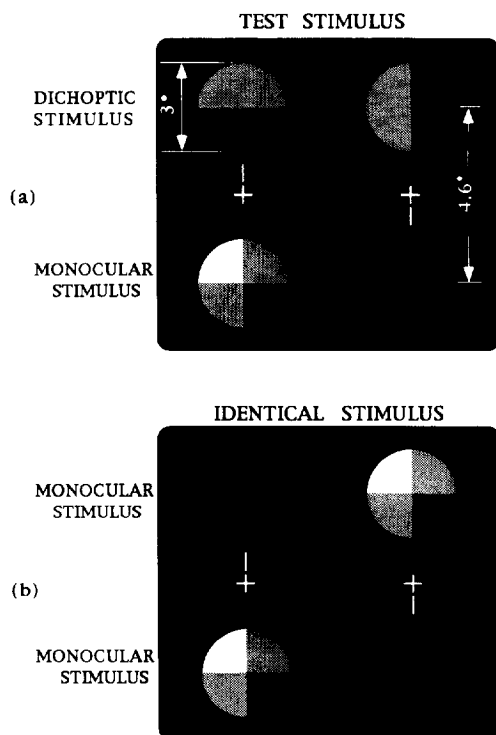**MONOCULAR STIMULUS**

(b)

MONOCULAR STIMULUS

FIGURE 1. Stimuli for contrast discrimination. (a) A test stimulus ("signal"). Each test stimulus contained a dichoptic stimulus and a monocular stimulus. The dichoptic stimulus was composed of a horizontal and a vertical edge of identical contrast. The monocular stimulus was composed of a pie-shaped pattern and a blank field whose luminance was the same as the mean luminance of the pie pattern. The two apertures on the left were shown to one eye and the two apertures on the right were shown to the other eye. The binocular view of the test stimulus was composed of two apertures, one contained a dichoptic pie pattern and the other contained a monocular pie pattern. The observer's task was to indicate whether the pie patterns in two fused apertures had the same contrast. In each constant stimulus experiment, the contrast of the dichoptic stimulus was kept the same and the contrast of the monocular pie pattern was set at different levels. Identical stimuli were intermingled with the test stimuli to assess the observers' sensitivity of contrast discrimination. An identical stimulus ("noise") is shown in (b). The lower pair and the upper pair were identical except in which eye seeing the pie pattern.

were presented within four circular apertures of the same size (3 deg in diameter, see Fig. 1). The two apertures on the left were seen by one eye and the two apertures on the right were seen by the other. Crosses and nonius lines between the apertures were used to facilitate binocular fixation and to monitor the convergence of the eyes. The binocular view of the stimulus consisted of two vertically aligned apertures on a dark background and a set of cross and nonius lines between these apertures. The mean luminance of the stimulus was 40 cd/m². Before each trial, the apertures were blank. After the observer pressed a key, the monocular and the dichoptic pie patterns were presented for 1.5 sec following a beep. When a monocular pie pattern appeared in the upper aperture the dichoptic pie pattern would appear in the lower aperture, or vice versa. The observer had to decide whether the patterns in the two fused apertures appeared to have the same contrast.

The dichoptic contrast referred to the Michelson contrasts of the horizontal and the vertical edges. They were always the same and were changed at the same time. The monocular contrast referred to the Michelson contrast between the brightest and the darkest points of the monocular pie pattern. The experiments were done in an otherwise dark room.

Procedure and data analysis

The method of constant stimuli was used to find a monocular pie pattern whose apparent contrast matched the apparent contrast of a dichoptic pie pattern. In one block of the experiment, a pair of orthogonal edges of a fixed contrast was compared with a monocular pie pattern that had one of the five or nine preset contrasts. The monocular contrast ranged from < 1 to 3 or 4 times of the contrast of the orthogonal edges. Each one of these monocular contrasts was paired with the same dichoptic stimulus to form a test stimulus [Fig. 1(a)]. Each test stimulus was presented 20-30 times. The presentation was randomized, in terms of which eye saw the horizontal edge, which eye saw the vertical edge, which eye saw the pie pattern and which eye saw the blank aperture. In order to estimate the observer's ability to discriminate contrast, 20-30 presentations of an identical stimulus were intermingled in the sequence of test stimulus presentation. The identical stimulus was composed of two identical monocular pie patterns [Fig. 1(b)]. The only difference between the two was which eye viewed the pie pattern. The observer responded to the stimulus sequence by pressing one of two keys. If the patterns in the two fused apertures appeared to have the same contrast, the observer pressed one key to accept it, otherwise he pressed another key to reject it. A feedback was given to the observer if an identical stimulus was rejected. One complication in this experiment was that stable dichoptic plaid could be perceived only at relatively low contrasts. When the contrast of the dichoptic stimulus was high, binocular rivalry became obvious and the pie pattern would disintegrate. In this case, both the contrast and the structure of dichoptic stimulus would look different from those of the monocular stimulus. In our experiments the observer was instructed to pay attention to both the structures and the contrasts of the pie patterns. The observers were instructed to reject a pair of stimuli if the structures and/or the apparent contrasts were different.

If we consider the test stimulus as a "signal" and the identical stimulus as a "noise", then we can use signal detection theory to analyze our data. If a signal was presented and the observer rejected it as having the similar contrast, that scored a "hit". If a noise was presented and the observer rejected it, that scored a "false alarm". In each block of the constant stimulus experiment, we obtained a common "false alarm rate" from the observer's responses to the identical stimulus. The false alarm rate was about 20% for all our observers. We also obtained a "hit rate" for each test stimulus. We could calculate a d' value for each test

stimulus used and generate a contrast discrimination function. A d' value close to zero would indicate that this particular monocular pie pattern could not be discriminated from the dichoptic pie pattern based on the apparent contrast. On the other hand, a d' value larger than unity would indicate that the dichoptic pie pattern appeared significantly different from the monocular pie pattern, either due to apparent contrast difference or due to structural difference or both. We used a program in Macmillan and Creelman's (1991) book to calculate the d' values.

The contrast discrimination experiment was conducted at dichoptic contrast levels 3%, 5%, 7% and 9%. Observers SS and PB were not tested with the 9% dichoptic contrast. Observer CS was only tested with the 3% dichoptic contrast. Each observer did one run of the constant stimulus experiment per condition.

Observers

Five observers participated in the experiments. Four of them (CS, SS, LC and LL) were experienced observers in binocular vision experiments. PB was a female work-study student on Berkeley campus. She was unaware of the purpose of the experiments. All observers had normal binocular vision and all wore their normal optical corrections during the experiments.

RESULTS

The shape of the contrast discrimination function

Figure 2 shows the contrast discrimination functions obtained from four observers. The vertical axis is the d' value and the horizontal axis is the contrasts of the monocular pie pattern in a constant stimulus experiment. Different symbols represent different dichoptic contrasts. For example, ● represents the condition where both the vertical and the horizontal edges have 3% contrast. For a given dichoptic contrast the d' value is high at some monocular contrasts but low at others. The shape of a discrimination function usually resembles the shape of an inverted bell. Most of the contrast discrimination functions have at least one point with a d' value that was close to zero. According to signal detection theory, a near zero d' value demonstrates an inability to discriminate the monocular pie pattern and the dichoptic pie pattern based on their apparent contrasts. For observer LC, the d' values on the contrast discrimination function for 9% dichoptic contrast are around unity. That means that under this condition, this observer can always discriminate between the dichoptic and the monocular pie patterns under this condition. As we have shown in our previous paper, the stable binocular combination of the dichoptic stimuli gave way to binocular rivalry at higher contrasts. Observer LC might have based his responses on the instability of the dichoptic stimulus at 9% dichoptic contrast.

The trough on the contrast discrimination function is usually located at a monocular contrast that is higher
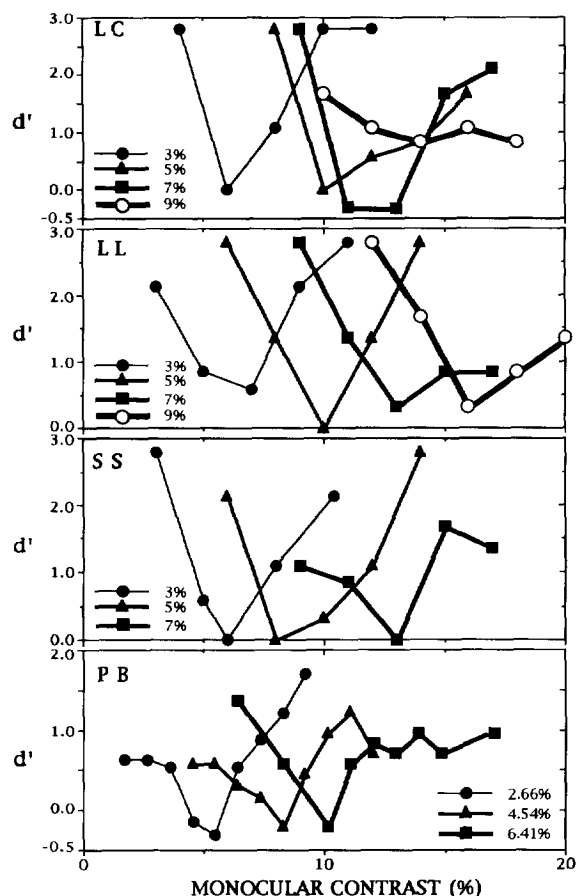

FIGURE 2. Contrast discrimination functions for four observers. The horizontal axis represents the contrast of the monocular pie pattern. The vertical axis is d' values (d' is the difference between the z-score of the "hit rate" and the z-score of the "false alarm rate"). A low d' value (near zero) indicates the inability to discriminate the contrasts of the two pie patterns in the test stimulus. In one block of a constant stimulus experiment, a dichoptic pattern of a given contrast was compared with five or nine levels of monocular contrast and thus generated a contrast discrimination function. Different symbols in the figures represent different dichoptic contrasts tested. Note that when the dichoptic contrast increases, the contrast discrimination function shifts to the right.

than the contrast of the dichoptic stimulus. For example, for observers LC and LL, when a 5% vertical edge was presented to one eye and a 5% horizontal edge was presented to the other eye (▲), the perceived contrast was similar to the apparent contrast of a monocular pie pattern of 10% contrast. In Fig. 3, we divide the monocular stimulus contrast with the dichoptic stimulus contrast and replot the d' data against this dichoptic contrast gain. The troughs of the discrimination functions of the four observers all cluster between contrast gains 1.5 and 2.0. Observer CS was only tested with 3% dichoptic contrast. The lowest d' value on his discrimination function was near zero and it also occurred at contrast gain of 2. We will discuss the meaning of this big dichoptic gain later.

Figure 2 illustrates that when the dichoptic contrast increases, the corresponding discrimination function also shifts to the right. Therefore the apparent contrast of the dichoptic pie pattern increases with the increasing
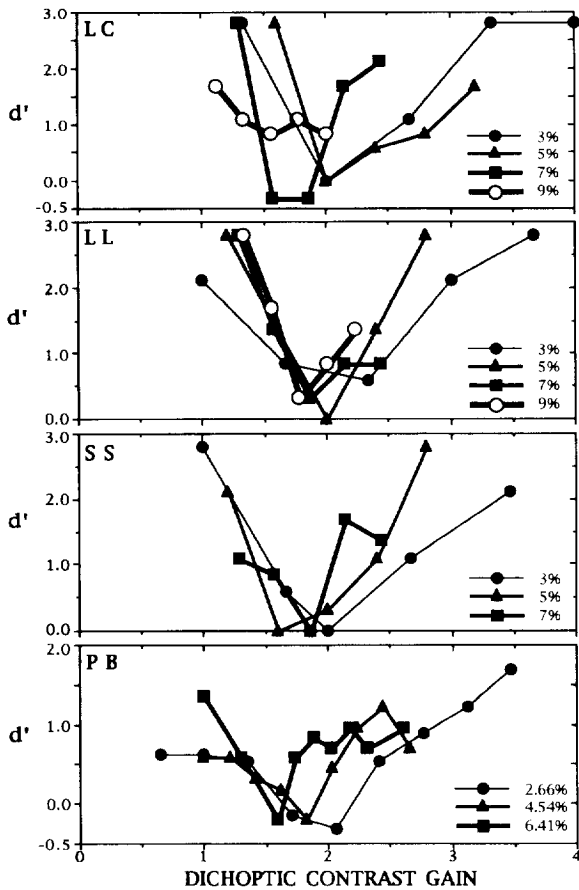
FIGURE 3. The data shown in Fig. 2 is replotted against the ratio of the monocular contrast and the dichoptic contrast. Because in our experiment, the apparent contrast of a dichoptic pattern is expressed in terms of the monocular contrast, the ratio of the monocular contrast and the dichoptic contrast is termed "dichoptic contrast gain". This plot shows that the best contrast matching between the dichoptic and the monocular pattern occurs at dichoptic contrast gains > 1.5. It also shows that the dichoptic contrast gain is high for low dichoptic contrast and it decreases with increasing dichoptic contrast.

contrast of the orthogonal edges. However, the perceived contrast increases at a lower rate than the increases of dichoptic contrast. This tendency is shown clearly in Fig. 3 where the troughs of the contrast discrimination functions spread to the left with increasing dichoptic contrast. This demonstrates that the great dichoptic contrast gain found at lower contrasts is diminishing at higher contrasts. For example, for LL the contrast gains of the troughs are 2.0, 1.86 and 1.78 when the dichoptic contrasts are 5%, 7% and 9% respectively. For PB, the troughs occur at 2.06, 1.83 and 1.59 when the dichoptic contrasts are 2.66%, 4.54% and 6.41%. The trough positions (the horizontal positions of the lowest points on the curves in Fig. 3) for the four observers are plotted against dichoptic contrast gain in Fig. 4. We conclude that dichoptic contrast gain is reduced when the contrast of the dichoptic stimulus increases. It seems that binocular suppression starts to show its effect by reducing the apparent contrast of the dichoptic pie pattern, even before it starts to destroy the stable percept of a pie pattern.

Discriminating dichoptic pie pattern from monocular pie pattern

We have shown that our observers could not discriminate a dichoptic pie pattern and a monocular pie pattern based on their apparent contrast. Could they discriminate between the two stimuli based on other available information? Blake et al. (1991) have shown that a dichoptic plaid could be discriminated from a binocular plaid in a forced-choice paradigm. We pointed out that their observers might base their discrimination on binocular luster that was obvious in dichoptic plaid but not in binocular plaid. In our experiments, a dichoptic pie pattern was paired with a monocular pie pattern that also appeared lustrous. Is discrimination possible using information other than binocular luster? Two observers (PB and LL) were tested using the same dichoptic and monocular pie patterns. The observers were shown the monocular and dichoptic stimuli before the experiment started and they were instructed to give a forced choice response indicating whether the upper or the lower binocular field contained the dichoptic stimulus. Dichoptic contrasts of 6.41% and 5% were used for PB and for LL respectively. In the first 100 or 200 trials, the rate of discrimination was around 50% for both observers, indicating a total confusion of dichoptic and monocular pie patterns. However, their performance improved with more practice and the discrimination rate stabilized at 70–80% after 500 trials. We therefore concluded that although both the dichoptic and the monocular pie patterns looked lustrous, there were still some subtle differences between the two stimuli that could be learned by the observers through practice and could be used in discrimination. We will provide an explanation in the Discussion section.
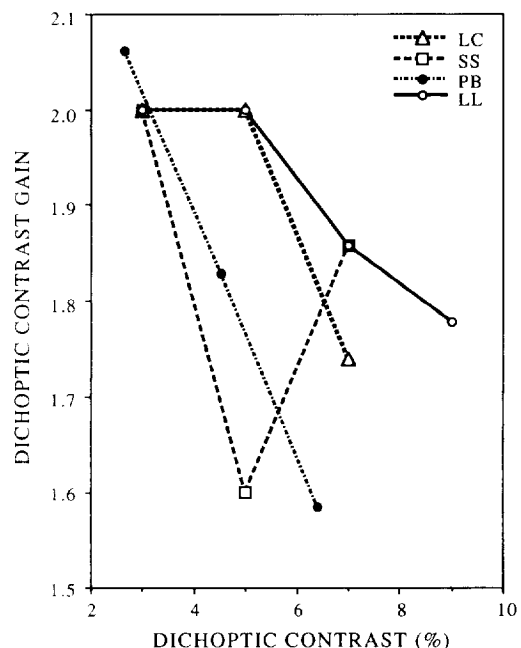

FIGURE 4. Each point in this graph was the trough position of a contrast discrimination function in Fig. 3. The plot shows the decay of the dichoptic contrast gain with increasing dichoptic contrast.

DISCUSSION

There have been several models about the rules governing binocular contrast summation between similar targets, such as the quadratic summation model of Legge (1984a, b) and the vector summation model of Birch (1979). There are at least two reasons that lead us to believe that these rules can not be applied to the binocular combination of orthogonal stimuli. First, the receptive fields of a binocular cortical cell have similar orientation and spatial frequency tuning (Hubel & Wiesel, 1962; Maske, Yamane & Bishop, 1984; Freeman & Ohzawa, 1990; Ohzawa, DeAngelis & Freeman, 1990). It has been shown repeatedly that two similar stimuli on the corresponding retinal regions can facilitate the responses of binocular cortical cells. Under optimal conditions, binocular response can be several times larger than either monocular response. However, there is very little evidence showing that grossly different stimuli can facilitate the response of a binocular cell. Ohzawa and Freeman (1986a, b) found that binocular cells in cat striate cortex gave responses that were several times larger than the best monocular responses when they were stimulated with gratings of similar orientations. However, the responses of these cells to a pair of orthogonal gratings remained at the level of the monocular response. Therefore, while binocular facilitation between two similar stimuli can be comprehended by the activities of single binocular cells, the dichoptic contrast gain we reported does not have its neural substrate at single cell level. This dichoptic gain needs to be looked at as a global contrast phenomenon. Second, stable binocular combination of similar stimuli can be maintained over a large range of contrast but this is not

true for dichoptic stimuli. Liu *et al.* (1992) showed that the dichoptic plaid perception became less stable when grating contrast was increased, and eventually at a high enough contrast, the component gratings started to rival. The rule for this type of binocular combination needs to reflect this transition from a stable combination to a less stable combination, to rivalry.

Binocular luminance averaging model

For the orthogonal edges employed in this study, the binocular combination was rather stable, and in most regions of the field binocular corresponding points were stimulated by uniform patches of unequal luminances. It has been shown in several experiments (de Weert & Levelt, 1974; Engel, 1969; Levelt, 1965) that if the luminances in the two eyes do not differ too much, the binocular brightness is determined by the simple average of the two monocular luminances. We can therefore assume that the same rule can be applied to our dichoptic stimulus and the apparent contrast of the dichoptic pie pattern is the result from a point-by-point binocular luminance average in the binocular field. Figure 5 shows the point-by-point luminance average in the dichoptic and monocular pie patterns. The numbers in the figure represent the indices of the color-look-up-table of the video card that are linearly related to the luminance on the monitor in the low contrast range. In the case shown in Fig. 5(a) the contrast of both the horizontal and the vertical edges is 6.25%. After a point-by-point average of the luminances, the contrast of the dichoptic pie pattern is again 6.25%. However, when the luminance average is taken between a 6.25% monocular pie pattern and a blank field with a luminance of 128, the luminance values are 124 and 132 in
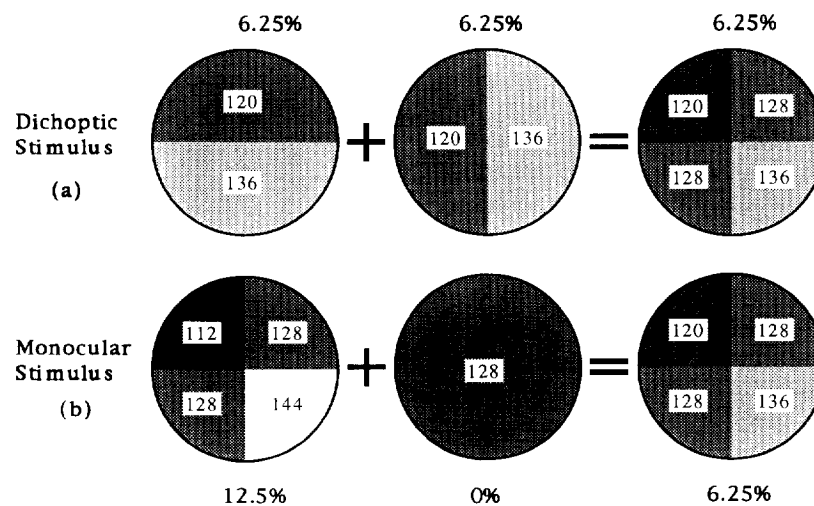

FIGURE 5. Binocular luminance averaging model assumes that binocular contrast is determined by point-by-point average of the luminance in each eye's stimulus. The numbers shown in the apertures can be regarded as the luminance values of the regions. According to this rule, the binocular combination of two 6.25% orthogonal monocular edges yielded a pie pattern of 6.25% (a). When a monocular pie pattern was combined with a blank field, the contrast of the monocular pattern had to be 12.5% in order to produce a 6.25% binocular contrast (b). Although this model predicted a monocular/dichoptic ratio of 2 when contrasts of the dichoptic and monocular stimulus match, it also predicted that blank field in one eye would reduce the perceived contrast of a pattern in the other eye, which does not agree with our everyday experience.

the darkest region (the second quadrant) and in the brightest region (the fourth quadrant) respectively. The resultant Michelson contrast of the monocular pie pattern is 3.125%. In order to match the apparent contrast of the dichoptic pie pattern, the contrast of the monocular pie pattern has to be increased. As shown in Fig. 5(b), the contrast of the monocular pie pattern has to be increased to 12.5% in order to produce 6.5% contrast after the point-by-point average with a blank field. Therefore, when the contrasts are not discriminable, the contrast ratio of the monocular pie pattern and the dichoptic pie pattern is about 2.0. This agrees with the results obtained under the most stable condition for the dichoptic pie pattern (Fig. 3). However, this apparent agreement between the luminance averaging model and the empirical data is questionable. The point-by-point luminance averaging model predicts that the apparent contrast of the binocular combination of a monocular pie pattern with a blank field will be reduced by half. This prediction does not agree with our daily experience. We can view a pie pattern either through two eyes or through one eye while the other eye is covered by a translucent patch. No obvious reduction of apparent contrast is perceived when we switch from two eyes to one eye. This observation has been used by the suppressionists to attack the fusion theory of binocular vision, which, in its early version, assumed that the light sensation from the two retinas was united in a point-by-point fashion. For example, von Helmholtz (1867), Verhoeff (1935) and Asher (1953) demonstrated convincingly that a black feature in one eye did not appear gray when it was paired with a white field in the other eye. From our knowledge about the neural information processing of the visual system, we know that neurons in the early visual pathways usually have structured receptive fields. Only figures of proper spatial frequency and orientation can elicit good responses. Most of the neurons will give no responses to uniform illumination of their receptive fields. Whether the monocular response to the blank field does not exist or it is totally suppressed by the monocular response to a figure in the other eye is an issue that is beyond the scope of this paper. The relevant observation is that when one eye views a figured field and the other eye views a blank field, the figured field dominates. Point-by-point averaging has proved to be an excellent model to describe light sensation when both eyes view blank fields of difference luminances. However, it cannot be applied to the contrast phenomena because it ignores the predominance of contours and edges over a uniform field.

Binocular contrast preservation model

The contour predominance over uniform luminance suggests another model for binocular combination of orthogonal contours. In a recent paper (Liu & Schor, 1994) we showed that binocular suppression was confined in a region surround the intersection of conflict contours. The size of this "suppression zone" was shown to shrink when the spatial frequency components of the

stimuli increased. If we assume that binocular inhibition is confined within a small area that surrounds the intersection of the sharp contours in Fig. 6, then the rest of the binocular field is comparable to a situation where a monocular edge in one eye is superimposed on a region of uniform luminance in the other eye. The monocular edge will be dominant in this region and it is likely that its contrast will be preserved. Therefore we may assume that when contrast matching is achieved, the apparent contrast of the dichoptic pie pattern is the result of preserving the contrast of each monocular edge. This requirement is easily satisfied. In Fig. 6 we assume that the luminances of the darker regions and the brighter regions of the two orthogonal stimuli are G_{min} and G_{max} respectively. The Michelson contrast of each of the orthogonal edge is

$$C_g = (G_{max} - G_{min})/(G_{max} + G_{min}).$$

Let's assume the luminance in the brightest region (the fourth quadrant) of the binocular field is P_{max}, which results from the superposition of two high luminance regions of the monocular stimuli; the luminance of the darkest region (the second quadrant) is P_{min} and the luminances of both the first and the third quadrants are M. The contrast preservation model requires that in the binocular field, the contrast on the border between the first and the second quadrant equals to the contrast of the vertical edge of the dichoptic stimulus (C_g)

$$(M - P_{min})/(M + P_{min}) = C_g.$$

The same relation should be held for the contrast on the border between the second and the third quadrant because the horizontal edge of the dichoptic stimulus has the same contrast as the vertical edge. The model also requires that the contrast on the other two borders satisfy the following relationship

$$(P_{max} - M)/(P_{max} + M) = C_g.$$

From these two equations we find

$$P_{min} = M*(1 - C_g)/(1 + C_g)$$

$$P_{max} = M*(1 + C_g)/(1 - C_g)$$

and the Michelson contrast of the dichoptic pie pattern is

$$C_p = (P_{max} - P_{min})/(P_{max} + P_{min})$$

$$= [(1 + C_g)^2 - (1 - C_g)^2]/[(1 + C_g)^2 + (1 - C_g)^2]$$

$$= 2*C_g/(1 + C_g^2).$$

Note that M does not show in C_p. The ratio of the contrast of the dichoptic pie pattern and the contrast of the orthogonal edge is

$$C_p/C_g = 2/(1 + C_g^2).$$

Note that according to the contrast preservation model, the contrast of a monocular stimulus (whether it is an edge or a pie pattern) is preserved when it is paired with a blank field. Therefore, when contrast matching occurs, the contrast of the monocular pie pattern should be equal to C_p. If the contrast of the monocular edges (C_g)

$$C_g = \frac{G_{max}^- - G_{min}}{G_{max}^+ + G_{min}}$$

$$C_p = \frac{P_{max}^- - P_{min}}{P_{max}^+ + P_{min}} \begin{cases} \frac{P_{max}^- - M}{P_{max}^+ + M} = C_g \\[2mm] \frac{M - P_{min}}{M + P_{min}} = C_g \end{cases}$$

$$\begin{cases} \frac{P_{max}^- - M}{P_{max}^+ + M} = C_g\,\alpha(C_g) \\[2mm] \frac{M - P_{min}}{M + P_{min}} = C_g\,\alpha(C_g) \end{cases}$$

$$\frac{C_p}{C_g} = \frac{2}{1 + C_g^2} \qquad\qquad \frac{C_p}{C_g} = \frac{2\,\alpha(C_g)}{1 + C_g^2 \alpha^2(C_g)}$$
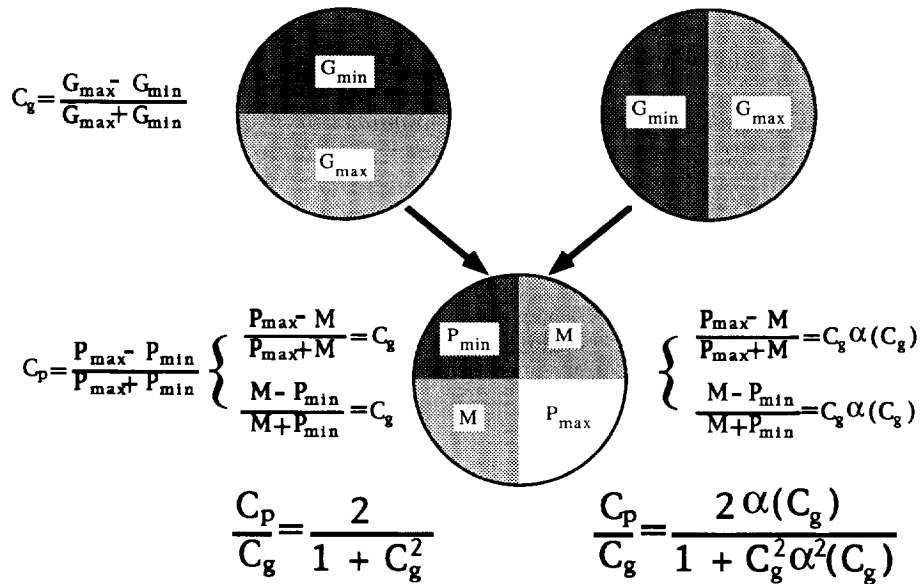
FIGURE 6. Binocular contrast preservation model assumes that the contrast of a monocular edge will be preserved if there are no rivalrous edges in the corresponding area in the other eye. When this requirement is satisfied, the binocular combination of two orthogonal edges of contrast C_g will produce a pie pattern of a contrast C_p. The combination of a monocular pie pattern and a blank field is not shown because the resultant contrast is the same as the contrast of the monocular pattern. When the contrasts of the dichoptic and monocular stimulus match, C_p/C_g is the dichoptic contrast gain. The formulae on the left are derived under the assumption that the contrasts of the monocular edges are perfectly preserved. The formulae on the right are derived under the assumption that binocular suppression attenuates the contrasts of the monocular edges by a factor of $\alpha(C_g)$.

equals 0.03, then the model will predict that the contrast ratio of the monocular and dichoptic pie patterns (C_p/C_g) equals 1.998. This contrast gain was found under the most stable conditions for dichoptic pie pattern (Fig. 3).

We also showed that when the contrast of the orthogonal edges C_g increased, the dichoptic contrast gain decreased (Fig. 4). The contrast preservation model does predict that C_p/C_g should decreases with increasing C_g, but the rate of decrease is too slow. For example, C_g will have to be 0.5 (50%) in order to obtain a contrast ratio of 1.6. But we see in Fig. 4 that contrast gain became 1.59 for PB when the dichoptic contrast was 6.41%. From our previous observations (Liu *et al.*, 1992) we know that binocular inhibition becomes stronger and the dichoptic plaid perception becomes less stable at higher dichoptic contrast. We can assume that one of the effects of the increasing binocular inhibition is to reduce the monocular contrast signal in each eye. In other words, the contrasts of the orthogonal edges of the dichoptic stimulus may not be completely preserved. If we take binocular inhibition into consideration, the contrast signal produced by each orthogonal edge under binocular viewing is no longer C_g, but rather it is C_g multiplied by an attenuation factor $\alpha(C_g)$, which is dependent on C_g. α has a maximum value of 1.0 and its value decreases with increasing C_g. Now

$$(M - P_{min})/(M + P_{min}) = C_g * \alpha(C_g)$$

and

$$(P_{max} - M)/(P_{max} + M) = C_g * \alpha(C_g)$$

and the dichoptic contrast gain becomes

$$C_p/C_g = 2*\alpha(C_g)/(1 + C_g^2 * \alpha^2(C_g)).$$

When C_g is low, there will be very little binocular inhibition, α will have a value very close to 1.0, monocular contrast signals will suffer very little attenuation, and C_p/C_g will be close to 2.0. When C_g increases, α value decreases, and so does C_p/C_g. When C_g is high enough, binocular rivalry will dominate the binocular field, and the dichoptic pie pattern will disintegrate. Data presented in Fig. 4 is insufficient to estimate the dependence of α upon C_g. In order to determine the function one has to repeat the contrast discrimination experiment at different dichoptic contrast levels and to add more datum points in Fig. 4.

The binocular contrast preservation model also complies with the physiological findings from Freeman–Ohzawa laboratory. The global contrast gain under dichoptic condition does not result from any increase in the activities of the binocular cells related to the dichoptic stimuli but rather from preserving their activities related to the monocular edges in the different regions of the binocular field. Under certain stimulus conditions, like the orthogonal edges used in our experiments, the perceived contrast is increased by the simultaneous contrast of these monocular edges.

The binocular contrast preservation model cannot be applied to the fusible stimuli used by Birch (1979) and Legge and Rubin (1981). These are adequate stimuli for binocular cortical cells. The contrast signals in the two eyes converge on the same binocular cell whose output represents the binocular contrast at a spatial point. The contrast summation observed with these stimuli is likely due to the increased activities of the binocular cells, rather than the contrast of the signals from two distinct channels.

The effect of fixation disparity

Finally, we get back to the question how could the observer discriminate between the dichoptic pie pattern and the monocular pie pattern. As we have argued in the Methods section, the purpose of using a monocular pie pattern instead of a binocular pie pattern in our experiment as a comparison was to eliminate binocular luster as a discrimination cue. However, after some practices the observers could reliably discriminate between the stimuli. We think there is yet another cue that might be discovered by the observers during practice and then be used to discriminate the pie patterns. In the binocular view, the vertical edge in the monocular pie pattern always bisected the horizontal edge. no matter where the two eyes were fixating. but this might not be true for the dichoptic pie pattern. Due to the imprecision of binocular fixation (fixation disparity) the apertures containing the horizontal and the vertical edges might slide a little relative to each other while binocular fusion of the apertures was maintained. In the binocular field. the monocular pie pattern would be perfectly symmetric about its aperture while the vertical edge of the dichoptic pie pattern might appear off center. Because the upper and lower apertures were close to each other (1.6 deg) on the screen and the apertures were not very large (3 deg). even a small offset would be easily detected and the offset could be used to identify the aperture that contained the dichoptic stimulus. Of course, there might be other unknown aspects in the appearance of a pair of dichoptic stimuli that can be used in discrimination.

In conclusion, the apparent contrast of a monocular pie pattern was compared with that of a dichoptic pie pattern in a series of psychophysical experiments. When the dichoptic contrast was low. the dichoptic pie pattern appeared to have the same contrast as a monocular pie pattern whose contrast was twice that of the dichoptic stimulus. However, the dichoptic contrast gain became less pronounced when the contrast of the dichoptic stimuli was increased, presumably due to the increased binocular inhibition. The monocular and the dichoptic pie patterns could still be discriminated even under the optimal conditions, but this discrimination might have nothing to do with the stability. the apparent contrast or the binocular luster of the stimuli. The observed dichoptic contrast gain was explained with a binocular contrast preservation model. which assumed that the contrast of a monocular edge was preserved in the binocular field when there were no conflicting contours in the corresponding area of the other eye.

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