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Binocular interactions in suprathreshold contrast perception

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Suprathreshold binocular contrast interactions were studied psychophysically. A split-screen CRT display was used to present separate sine-wave gratings to the observer's left and right eyes. The method of constant stimuli and a modified method of adjustment were used to find sets of binocular *test* patterns that matched a given binocular *standard*. Test patterns consisted of the simultaneous presentation of sine-wave gratings that differed in contrast to the left and right eyes. Standard patterns consisted of identical sine-wave gratings presented to the two eyes, and had the same spatial frequency as the test patterns. Binocular contrast matching functions were obtained for several standard contrasts at 1 and 8 c/deg. Binocular matching functions were obtained for luminance increments as well. The binocular contrast matching functions departed from a simple binocular averaging rule, and behaved as if the eye receiving the higher contrast disproportionately dominated the binocular contrast percept. Departures from the binocular averaging rule were slightly greater for higher standard contrasts. Spatial frequency had little effect, and the luminance increment matching functions also departed from the binocular averaging rule. There was evidence for a contrast version of Fechner's paradox and for substantial individual differences in a form of ocular dominance. In a further experiment, additivity of suprathreshold binocular contrast summation was examined by testing the double-cancellation condition. We found no systematic violations of additivity at 1 and 8 c/deg. Models of suprathreshold binocular contrast summation were examined.

How do the two eyes interact in the perception of contrast? Stereopsis is one form of interaction. Binocular summation is another. This paper is concerned with the latter.

The term *binocular summation* is used generically to refer to any visual process by which inputs to the two eyes are combined in detection, recognition, or magnitude judgments. The phrase does not necessarily imply simple addition as the means of combination, although some models of binocular summation include forms of additivity.

Over the years, there have been many studies of binocular summation in the detection of luminous stimuli. It is well established that binocular thresholds for the detection of spots of light are lower than monocular thresholds. Pirenne (1943) concluded that binocular summation at threshold was no more than would be expected if a signal were detected when it exceeded the threshold of either of two independent detectors. He termed this form of binocular summation *probability summation*. However, Thorn and Boynton (1974) have shown conclusively that stimulation of corresponding retinal points reduces binocular threshold more than would be expected from probability summation. They concluded that binocular summation at threshold must be due in part to *neural summation*. An extensive review of the literature led Blake and Fox (1973) to the same conclusion.

Neural summation is also reported for detection of sine-wave gratings. Contrast sensitivities for gratings viewed binocularly are about 40% greater than corresponding monocular sensitivities (Campbell & Green, 1965a; Bacon, 1976; Blake & Levinson, 1977; Braccini, Gambardella, & Suetta, 1980). The mechanism of neural summation at contrast threshold appears to be spatial frequency and orientation selective (Bacon, 1976; Blake & Levinson, 1977).

Suprathreshold binocular interactions have been extensively studied but are less well understood. Binocular summation in the perception of luminance has been investigated in matching experiments (Aubert, 1865, cited by Levelt, 1965; De Silva & Bartley, 1930; Engel, 1970; Fry & Bartley, 1933; Levelt, 1965; Sherrington, 1906), in reaction time experiments (Gilliland & Haines, 1975; Minucci & Connors, 1964; Poffenberger, 1912), and in brightness estimation experiments (Curtis & Rule, 1978; Engel, 1967; Stevens, 1967). All three classes of experiments tend to support the conclusion that a bin-

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ocularly viewed luminance source produces visual effects very much like a monocular source with a 30% to 70% higher luminance.

In his extensive series of binocular luminance matching experiments, Levelt (1965) found brightness matches between a *test* stimulus and a *standard* stimulus. The standard consisted of identical disks of equal luminance presented in register to the two eyes. The test pattern consisted of a disk of fixed luminance presented to one eye and a disk of adjustable luminance presented in register to the other eye. The observer's task was to adjust the luminance of the latter so that the test stimulus matched the standard. Matches of this sort were found for various luminances of the fixed test component. The resulting "equal-brightness" curves represent test pairs of left- and right-eye luminances whose binocular combination appears equally bright. Three important results emerge from Levelt's study. (1) When the luminance of the fixed component of the test pattern is not extremely different from the standard stimulus, binocular combinations of equal brightness obey a *binocular averaging* rule—that is, the binocular brightness of the test and standard stimuli are judged equal when the average luminance of the two test components is equal to the average luminance of the standard components. (2) When the luminance of the fixed test component is zero, or very small compared with the standard, binocular averaging does not occur, and *Fechner's paradox* results[1]—that is, small increases in the low-luminance test component require that the luminance of the adjustable test component also be increased to maintain the equal brightness. (3) The contribution of each monocular component to the binocular percept is influenced by individual variations in "ocular dominance" and by the amount of monocular contour in the test patterns.

Suprathreshold binocular contrast interactions have been studied in reaction-time experiments (Blake, Martens, & Di Gianfilippo, 1980; Hawerth, Smith, & Levi, 1980) and in contrast masking experiments (Legge, 1979; Levi, Harwerth, & Smith, 1979). In their reaction time study, Harwerth et al. (1980) found the contrasts of gratings, presented either monocularly or binocularly, that produced a criterion response latency. Near contrast threshold, monocular gratings required 40% to 70% more contrast than binocular gratings. At higher contrasts, there were wide individual differences. Some observers required significantly more contrast for monocularly viewed gratings, while others required less contrast.

Masking experiments indicate that binocular interactions in suprathreshold contrast processing are also spatial frequency and orientation selective. Legge (1979) measured threshold contrast for test gratings in one eye in the presence of masking gratings in the same eye (monocular masking) or contralateral eye (dichoptic masking). When the test and masking frequencies were identical, test thresholds were greatly elevated. Surprisingly, dichoptic maskers produced greater threshold elevation than monocular maskers. It is apparent from these results that a suitable high-contrast grating presented to one eye substantially reduces contrast sensitivity in the contralateral eye.[2]

The existence of dichoptic contrast masking is reminiscent of contour effects found by Levelt (1965) in his studies of binocular brightness matching. Levelt found that increasing the amount of "contour" in the stimulus presented to one eye increased the dominance of that eye in the weighted averaging of binocular brightness.

These studies demonstrate the existence of strong binocular interactions in suprathreshold processing. However, they do not directly address how perceived binocular contrast depends on the component monocular contrasts. If binocular contrast perception behaves like binocular brightness perception, it might be expected to obey an averaging rule. However, if the presentation of unequal contrasts to the two eyes leads to a dominance by the eye viewing the higher contrast pattern, it might be expected that the binocular contrast percept would be disproportionately dependent upon this eye's input.

The experiments of this paper were undertaken to examine how component monocular contrasts combine to produce a binocular contrast percept. To what extent does suprathreshold binocular summation in contrast perception parallel binocular summation in brightness perception? Do contrast matches obey a binocular averaging rule? Does a version of Fechner's paradox hold for binocular contrast perception? Are there individual differences in binocular contrast perception manifested by differences in ocular dominance?

We addressed these questions with experiments conducted at three spatial frequencies and at several contrast levels. We also tested the hypothesis that binocular summation is an additive process.

METHOD

Apparatus

Vertical sine-wave gratings were produced on an HP 1300A CRT display by Z-axis modulation (Campbell & Green, 1965b). The display had a P31 phosphor, a constant mean luminance of 10 cd/m², and a dark surround.

The resolution and contrast response of the CRT were measured with a narrow slit and a UDT 80X Opto-meter. Contrast is defined as (Lmax − Lmin)/(Lmax + Lmin), where Lmax and Lmin are the maximum and minimum luminances in the sinusoidal luminance distribution. During the experiments, grating contrasts were kept within the CRT's linear region. (In the luminance increment-matching experiment, some settings fell outside the linear range, but the nonlinearity of the CRT's response was taken into account.)

Split-screen viewing was arranged so that the left and right eyes could be stimulated with different patterns. A vertical, black divider extended from the center of the display to the observer's

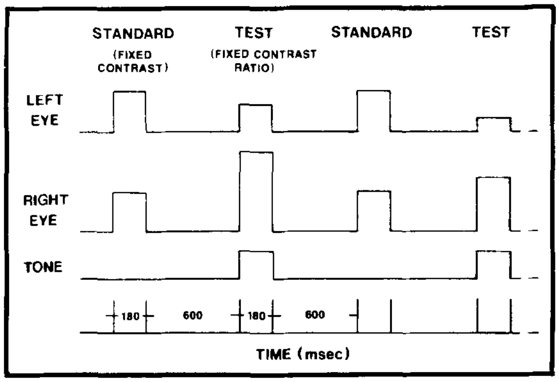

Figure 1. Schematic diagram of the stimulus sequence within a trial.

nose. Black fixation dots and vertical nonius lines were placed at the centers of the half fields, to aid in precise binocular alignment. To help convergence and to regulate head position, observers viewed the display with base-out prisms mounted in trial frames attached to the divider. Spectacle lenses were selected so that the observers could comfortably converge and accommodate on the fixation marks. Observers were instructed to be sure that the nonius lines appeared in vertical alignment and that the fixation dots were fused before making a response.

Figure 1 shows the stimulus sequence. A trial consisted of sequential presentations of a *standard* stimulus and a *test* stimulus. Both were presented for 180 msec, separated by 600 msec. Except for the method of constant stimuli, described below, standard and test patterns continued to alternate until the observer made a setting. The standard consisted of identical sine-wave gratings presented to the two eyes. The test stimulus consisted of right-eye and left-eye sine-wave grating components having the same spatial frequency as the standard. However, the contrasts of the right- and left-eye components of the test stimulus were often unequal. All stimuli were in cosine phase with the fixation marks.[3]

Sine-wave voltages were produced by an HP 3312A function generator. The output of the function generator was routed through two separate signal pathways. The two pathways converged on a two-input, one-output electronic switch whose output was applied to the Z-axis. A pulse, synchronized with the horizontal sweep of the CRT, controlled switch closure in such a way that one of the signals determined the pattern on the left half of the display while the other determined the pattern on the right half of the display. An LSI-11/2 computer and two 12-bit D/A converters controlled the signal voltages, and hence contrasts, through analog multipliers in each channel. Observers entered their responses by keypresses. The computer sequenced trials, collected responses, and analyzed the data.

Some early data were collected with analog equipment. Signal amplitudes were controlled by decibel attenuators. Timing was done by a series of electronic switches, linked together in a timing chain. Observers adjusted test contrast by turning a hand-held potentiometer. Observations made with this apparatus were satisfactorily replicated on the computer-controlled apparatus.

Procedure

Experiments were performaed at 1 and 8 cycles/degree (c/deg). An experiment was also performed with luminance increments of the uniform fields (0 c/deg). For the 1-c/deg gratings and the luminance increments, the viewing distance was 57 cm and the half fields subtended 12 deg horizontally × 20 deg vertically. For the 8-c/deg gratings, the viewing distance was 228 cm and the half fields subtended 3 × 5 deg.

Contrast matching by the method of constant stimuli. The method of constant stimuli was used to find a pair of right- and left-eye test contrasts that matched a standard. For a fixed contrast of the standard grating (e.g., .1) presented to both eyes, one componet of the test stimulus was also fixed in contrast (e.g., left-eye contrast of .02). A set of nine contrasts was chosen, any one of which could be selected for the contralateral test component (e.g., nine right-eye test contrasts that ranged from .09 to .13). In each of 360 trials, one of the set of nine possible test stimulus pairs was selected at random. Standard and test pairs were presented in random order. The observer pressed one of two keys indicating which interval contained the higher contrast pattern. By interpolation from the results, a pair of test contrasts could usually be found that was equally often judged to have a binocular contrast greater than or less than the standard's binocular contrast. This pair of test contrasts was regarded as making a binocular contrast match to the standard. In some cases, no match could be found.

In a single 2-h session, two sets of data of this kind were collected in interleaved fashion, one with the fixed test contrast seen by the right eye and the other with the same fixed test contrast seen by the left eye.

Contrast matching by the method of adjustment. The method of constant stimuli is reliable and accurate, but quite time-consuming. The method of adjustment is faster, and was used also.

The same stimulus sequence was used in an adjustment trial. During the trial, the test stimulus alternated with the standard until a match was made. The observer could raise or lower the test contrast, but the ratio of right- to left-eye test contrasts remained constant. The observer's task was to adjust the test stimulus, by pressing a key that changed the contrast in logarithmic steps, until it matched the standard stimulus in perceived contrast. The observer was instructed to use a bracketing technique.

For a given standard stimulus, characterized by its spatial frequency and contrast, there were 21 test stimuli. Test stimuli ranged from monocular presentation to the right eye (0 contrast to the left eye), through equal contrasts presented to the two eyes, to monocular presentation to the left eye.

A 1-h session was devoted to a single standard. Each of the 21 test stimuli was presented twice, with the order randomized. Data from four such sessions were combined so that the points in Figures 3-7 are arithmetic means of eight such settings.

Additivity test. The joint effect, B(L,R), of two independent variables, L and R, is *additive* if and only if B(L,R) = G(L) + H(R) for some real-valued functions, B, G, and H. We will call any other rule for combining the variables L and R an *interactive* rule. For example, in the relation B(L,R) = MAX(L,R), the effects of L and R are interactive, not additive.

Conjoint measurement theory (Falmagne, 1976; Krantz, Luce, Suppes, & Tversky, 1971; Luce & Tukey, 1964) provides a means for testing for violations of additivity in binocular contrast processing. If the joint effect of two monotonically increasing variables is additive, combinations of these variables will obey *monotonicity* and *double cancellation* rules. The following notation will be adopted to describe these rules in the context of a binocular contrast matching experiment. For left- and right-eye contrasts L_i and R_j:

> $L_1(R_1;L_2,R_2)$ is an estimate of L_1 (and will be abbreviated $\hat{L}_1$), the contrast which completes the match of (L_1,R_1) and (L_2,R_2).

Monotonicity requires that $\hat{L}_1$ be strictly decreasing in R_1 and strictly increasing in L_2 and R_2. In the matching experiment, an increase in either L_2 or R_2, or a decrease in R_1, would necessitate an increase in L_1 to maintain a match between (L_1,R_1) and (L_2,R_2). The binocular contrast matching data was examined to determine whether this condition holds.

The double cancellation rule is as follows.

> For ordered pairs of left and right contrasts (L_i,R_j), whenever $B(L_1,R_1) \leqslant B(L_2,R_2)$ and $B(L_3,R_2) \leqslant B(L_1,R_3)$, then $B(L_3,R_1) \leqslant B(L_2,R_3)$.

Falmagne's (1976) *cancellation rule* is the random conjoint measurement counterpart of double cancellation adapted for a matching experiment. The cancellation rule states that:

$$\text{for } L_1(R_1;L_2,R_2) = \hat{L}_1, \text{ then } L_3(R_2;\hat{L}_1,R_3) = L_4(R_1;L_2,R_3).$$

Tests of the cancellation rule were conducted at 1 and 8 c/deg. Within a trial, the test pattern alternated with the standard, as in the method of adjustment. However, one component of the test stimulus was fixed in contrast, and the observer adjusted the other component until the binocular test stimulus matched the standard. (The initial contrast of the adjustable component was set randomly above or below the standard contrast.)

A three-step procedure was used to test the cancellation rule, as illustrated in Table 1. In the table, *s mark the adjustable component for a given step. In one session, a set of one left-eye and three right-eye contrasts was selected. L_2 and R_2 were always equal, and R_1 and R_3 were less than and greater than R_2, respectively. For the first step of the procedure, L_2 and R_2 were presented as the standard contrast pair and R_1 served as the fixed test component. Observers made 91 or more adjustment settings for L_1, and the median was taken as the estimate of $\hat{L}_1$. In the second step, $\hat{L}_1$ was paired with R_3 as the standard, along with the fixed test component, R_2. At least 41 matches were made by the observer, and the median was taken as the estimate of L_3. In the final step, L_2 and R_3 were the standard pair, and R_1 was the fixed test component. The same number of adjustments was made as in the second step, and the median was taken as an estimate of L_4. We sought to maximize the sensitivity of our additivity test by requiring our subjects to make as many settings in the three-step procedure as they could manage in a single session without undue fatigue.

A median test (Mann-Whitney U test; Siegel, 1956) was used to test the null hypothesis that $L_3 = L_4$. Rejection of this hypothesis indicates a violation of the cancellation rule rejecting additivity of binocular contrast summation.

Observers

Six observers, all in their 20s, participated in the experiments. All were emmetropic except for A.W., who was optically corrected throughout. All observers had normal color vision and normal stereopsis. Threshold contrasts were measured for each eye by a two alternative forced-choice staircase procedure (see Legge, 1979), and were found to be normal—approximately .004 at 1 c/deg and .006 at 8 c/deg.

RESULTS

Two Methods for Measuring Binocular Contrast Matching

A common method for obtaining binocular matches (see, e.g., Levelt, 1965) has been to fix one component of a binocular test pair and have the observer vary the other test component until the binocular combination matches some standard stimulus. In the case of binocular contrast matching, the right-eye test contrast might be set at some fixed level and the observer required to adjust the left-eye's test contrast until the perceived contrast of the binocular test stimulus matches the perceived contrast of the binocularly viewed standard stimulus. A plot of left-eye test contrast vs. right-eye test contrast so obtained constitutes an equal perceived contrast curve. Although this technique has been successful in binocular brightness matching studies, we experienced some difficulty with it in pilot studies of binocular contrast matching. In some cases, unique matches could not be made and a large range of adjustable test contrasts provided acceptable matches. To deal with this problem, we used two other techniques, the method of constant stimuli and a modified method of adjustment.

Table 1
Cancellation Test Procedure

Step	Test Left	Test Right	Standard Left	Standard Right
1	L_1 *	R_1 .04	L_2 .1	R_2 .1
2	L_3 *	R_2 .1	$\hat{L}_1$ $\hat{L}_1$	R_3 .2
3	L_4 *	R_1 .04	L_2 .1	R_3 .2

**Adjustable component in test pair.*

Figure 2 shows data for two observers at 1 c/deg, collected by the method of constant stimuli. The standard stimulus consisted of identical left and right gratings with .1 contrast. The test stimulus consisted of a *fixed* component and a *variable* component. The fixed test component was a grating of fixed contrast, seen by one eye. The variable test component was a grating seen by the other eye, having one of nine contrasts.

Within a trial, one of the nine binocular test stimuli was randomly selected and paired, in random order, with the standard. The observer simply reported whether the first or second stimulus he saw appeared to have higher contrast. The symbols in Figure 2 represent the percentage of trials in which a particular test combination was reported as having a greater perceived contrast than the standard. For each observer, four of these psychometric functions are shown—fixed test component contrasts of .02 and .11, seen by either the left or the right eye. Each symbol is based on 40 trials. Maximum likelihood estimates of the best-fitting cumulative normal distributions through the sets of data were computed (Chandler, Note 1). They are drawn in Figure 2 for the cases in which the fixed contrast was .02. When the fixed test contrast was .11, the data were not well fit by cumulative normals; line segments have been drawn in Figure 2 to join members of a set. All the data for one curve were collected in one session. The fixed and variable component test contrasts at the 50% point on these curves may be taken as a binocular combination that matches the standard.

These psychometric functions fall into two cate-

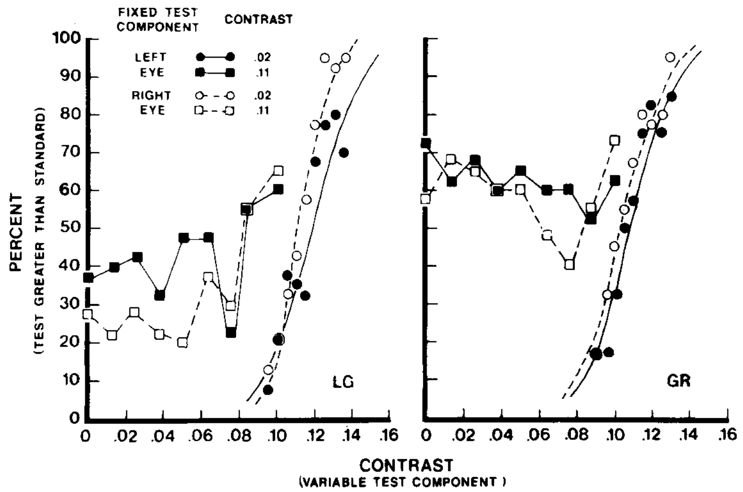

Figure 2. Psychometric functions. The graph presents the percentage of times a test stimulus with *fixed test component* contrast of .02 (circles) or .11 (squares) was judged to have greater contrast than the standard stimulus (contrast .1) as a function of the contrast of the *variable test component*. Standard and test stimuli were 1-c/deg sine-wave gratings. Normal ogives have been fit to the sets of circle data, and line segments have been drawn to connect the squares within a set. Each psychometric function is based upon approximately 360 trials. Open and filled symbols show data for which the fixed test component was presented to right and left eyes, respectively. Points lying near 50% represent test patterns that form a binocular contrast match to the standard. Left panel: Observer L.G. Right panel: Observer G.R.

gories. When the fixed test contrast was less than the standard contrast, for example, a fixed test component of .02, the observer's judgments were highly dependent upon the contrast of the variable test component. As a result, the psychometric functions are regular and steep. For instance, for observer G.R., the two steep psychometric functions are fit by normal ogives with means and standard deviations of .109 ± .019 and .105 ± .019. Comparable values for L.G. are .118 ± .020 and .112 ± .013. These data indicate that when a fixed test component has a contrast of .02, a variable test contrast of slightly more than .1 is required for the binocular combination to match the standard. When the variable test contrast is much greater than .1, the test stimulus is always regarded as having a higher perceived contrast than the standard. When the variable test component has a contrast much less than .1, the test stimulus is usually judged to have a perceived contrast that is less than the standard's. Similar results were obtained for other fixed test contrasts of less than .1 (the standard contrast).

The situation is very different when the fixed test contrast is greater than the standard contrast, for example, a fixed test contrast of .11. In this case, observers' judgments appear to be almost unrelated to the contrast of the variable test component. The curves are jagged and sometimes cross the 50% level more than once. Because these curves are so irregular, it would be very difficult to use them to find a unique test pair that matches the standard. In fact, there may be a large range of variable test contrasts which, when paired with the fixed test contrast, forms an acceptable match to the standard. This property of binocular contrast matching reduces the precision of the adjustment procedure when one test component is fixed at a contrast greater than the standard's and the observer varies the other test component to make a match. Figure 2 indicates that occasions will arise in which unique matches are difficult or impossible to find. This prediction was confirmed in pilot studies.

In Figure 2, the oscillations in L.G.'s shallow psychometric functions appear to be somewhat correlated. However, upon retest, oscillations of about the same amplitude but with somewhat different shape were found. For both observers, the shallow psychometric functions begin to rise more steeply for the highest variable test contrasts.

The psychometric functions of Figure 2 strongly suggest that binocular contrast matches are disproportionately dependent upon the high-contrast component in the binocular combination. If binocular averaging occurred, all the psychometric functions in Figure 2 would be expected to have the same steepness.

In light of these results, we used a *modified method of adjustment* to obtain most of our binocular matches. Instead of holding contrast constant in one eye and varying the contrast in the contralateral eye until a match to the standard was found, the observer adjusted the test contrasts presented to both eyes while their ratio was kept constant. Data of this sort are shown for observer G.R. as the open and closed circles in Figure 3. The two sets of data were collected several months apart, and each point is the mean of eight such settings. The standard was a 1-c/deg grating with a contrast of .1.

In Figure 3, symbols represent the combinations of left- and right-eye test contrasts that match a standard grating. The contrasts along the axes are given as percentages of the standard's contrast. Increasing right- and left-eye test contrasts while holding their ratio constant corresponds to moving outward along a radius through the origin. Accordingly, if error bars were shown, they would not be vertical, but would lie along these radii. Standard errors of the eight settings were small, typically in the range of 3% to 7%.

Three solid curves are shown in Figure 3, and in subsequent figures, for purposes of comparison. They represent three possible rules for binocular summation. When a match is made, suppose that the left and right monocular test contrasts, C_L and C_R, are related to the standard binocular contrast C_0 by

$$(C_L)^n + (C_R)^n = 2(C_0)^n = \text{constant}.$$

In the case of linear summation, n = 1, and

$$C_R + C_L = 2C_0, \qquad (C_R + C_L)/2 = C_0.$$

We call this the *binocular averaging* rule. It is plotted as the oblique line from upper left to lower right in Figure 3.

When n = 2,

$$(C_R)^2 + (C_L)^2 = 2(C_0)^2.$$

This rule of combination is variously known as *quadratic summation* or *orthogonal summation*. It is represented by the circular contour in Figure 3. Note that this rule exaggerates the overall importance of the high-contrast component of the test pair, in the sense that a small change in the contrast of the high-contrast component has a greater effect upon the overall perceived contrast than does a comparable change in the low-contrast component.

As the value of n in the power summation increases beyond 2, the relative importance of the high-contrast member of the pair grows larger and larger. In the limit, as n grows to infinity, a power summation formula predicts that the match will be determined solely by the high-contrast member of the pair and the data will fall along the horizontal and vertical solid lines at 100 in Figure 3. In this sense, the binocular matches are said to be *monocularly dominated* (not to be confused with "ocular dominance," which is discussed below).

The exponent n in the power summation formula may be used as an index indicating whether the inputs to the two eyes contribute proportionately, as in binocular averaging (n = 1) or whether the match is monocularly dominated by the eye receiving the higher contrast input (n > 1). The index n in the power summation formula is a convenient empirical description of the relative contributions of the two eyes in binocular matching. However, we shall see below that other rules of binocular summation provide reasonable accounts of the binocular contrast matching data as well. Therefore, we will take the index n and the three curves in Figure 3 as bench marks, not as necessarily implying the underlying form of binocular interaction.

In Figure 3, most of the data lie inside the quadratic summation curve. This indicates a very large deviation from binocular averaging and a high degree of monocular dominance.

The Xs in Figure 3 are contrast matches determined by the method of constant stimuli. Comparisons of the three sets of data indicate reasonable

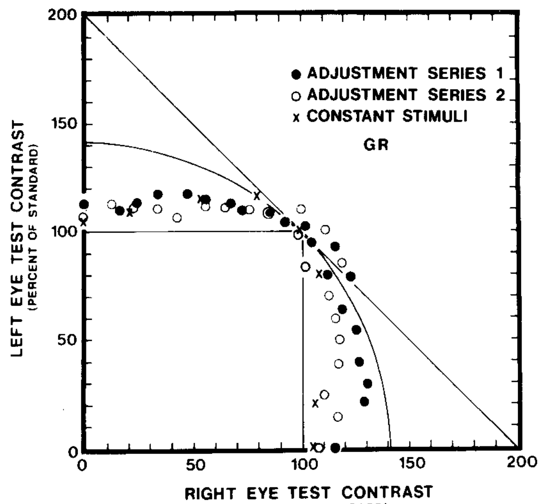

Figure 3. Binocular contrast matching functions obtained with two methods. Points represent the contrasts of left-eye test-grating components (ordinate) and right-eye test-grating components (abscissa) whose binocular sum appeared to match a standard pattern consisting of identical 1-c/deg sine-wave gratings of .1 contrast presented to both eyes. Test component contrasts are plotted on the axes as percentages of the standard grating's contrast. Data from three experiments are shown for Observer G.R. ● :Method of adjustment, Series 1. O: Method of adjustment, Series 2, in which data were collected several months after those of Series 1. Each of the circles represents the mean of eight adjustment settings ×: Symbols are 50% points taken from normal ogives fit to psychometric functions collected by the method of constant stimuli. The solid curves represent hypothetical rules for describing binocular summation (see text).

agreement between methods (adjustment and method of constant stimuli) and between repeated measurements after several months by the same method (Series 1 and Series 2). This agreement encouraged us to use the method of adjustment because of its much greater time efficiency. Data in all subsequent figures were collected by this method.

Binocular Contrast Matches at 1 c/deg

Figures 4a and 4b present binocular contrast matching data at 1 c/deg for Observers G.R. and A.W., respectively. In each case, four sets of data are shown, corresponding to standard contrasts of .005, .01, .1, and .5.

For both observers, the data segregate into two groups. For the high-contrast standards, .1 and .5, the contrast matches seem to lie inside the quadratic summation contour, indicating a power summation index greater than 2. This means that the perceived binocular contrasts are dominated by the high-contrast member of the test pair. For the low standard contrasts, .005 and .01, the data of G.R. lie on or outside the quadratic summation curve, suggesting that the eyes contribute more equitably to the binocular contrast percept. The low standard contrast data of observer A.W. also lie further from the origin than the high standard contrast data, but the effect is less marked. In addition, A.W.'s data exhibit a form of ocular dominance. A.W.'s data exhibit a higher summation index when the high-contrast member of the test pair was presented to the left eye than when the high-contrast component was presented to the right eye. Ocular dominance effects will be considered in greater detail in a later section.

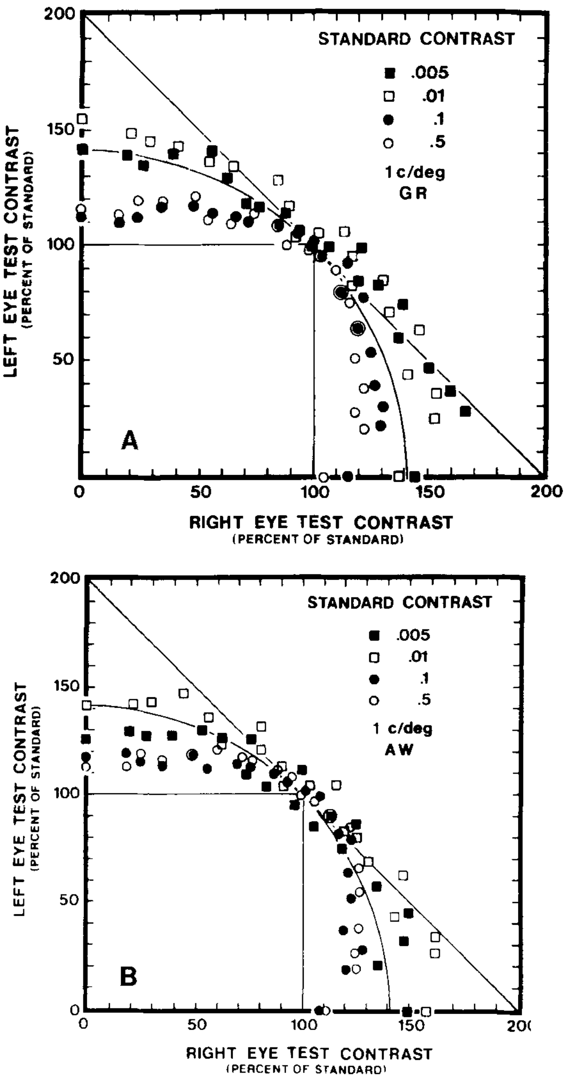

Figure 4. Binocular contrast matching functions at 1 c/deg. Points represent left and right-eye contrasts for 1-c/deg gratings whose binocular sum appeared to match a standard consisting of identical 1-c/deg gratings presented to both eyes. Results are shown for standard gratings having contrasts of .005 (■), .01 (□), .1 (●), and .5 (○). Each point is the mean of eight adjustment settings. (a) Observer G.R. (b) Observer A.W. Other details as in Figure 3.

Binocular Contrast Matching at 8 c/deg

Figures 5a and 5b show binocular matching data at 8 c/deg for Observers G.R. and D.K., respectively. The three sets of data correspond to standard contrasts of .01, .1, and .3.

G.R.'s data, Figure 5a, at 8 c/deg show a weaker version of the contrast effect evident at 1 c/deg. The triangles, corresponding to the standard contrast of .3, show a slightly higher summation index than the closed and open circles corresponding to standard contrasts of .1 and .01. D.K.'s data, Figure 5b, also show a slight contrast effect, but only when the high-contrast test component was presented to the right eye.

The contrast matching curves at 1 and 8 c/deg deviate more from binocular averaging (summation index of 1) than the binocular brightness matching curves reported by Levelt (1965). But our results are comparable to those reported by Birch (1979), who used a different matching procedure. Her observers adjusted the contrast of one member of a pair of dichoptically presented test gratings until the perceived contrast of the test pattern matched the perceived contrast of a standard binocular grating. For sine-wave gratings of 1 and 5 c/deg, Birch reported quadratic summation (summation index of 2). Unlike the present results, the shape of her contrast matching curves was independent of standard contrast.

Binocular Luminance Increment Matching

Measurements that were analogous to those described for binocular contrast matching were taken for luminance increments of the test fields. In the

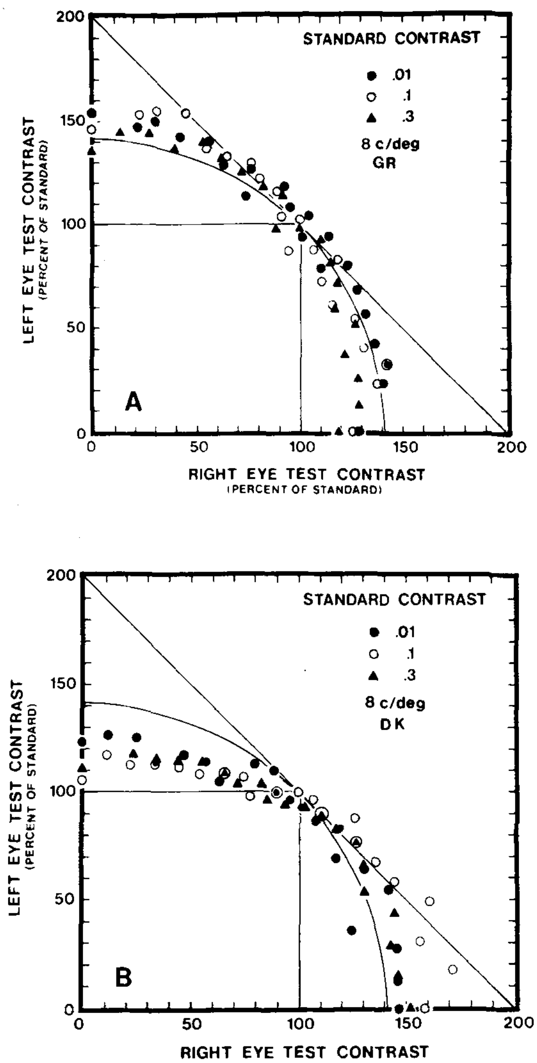

Figure 5. Binocular contrast matching functions at 8 c/deg. Details as in Figure 4 except that 8-c/deg gratings were used and the standard gratings had contrasts of .01 (●), .1 (○), and .3 (▲). (a) Observer G.R. (b) Observer D.K.

luminance increment experiment, the screen remained at 10 cd/m² between trials. The standard stimulus (see Figure 1) consisted of equal luminance increments of the half fields. In Figure 6, the three sets of data correspond to standard increments of .2, 1, and 5 cd/m². The test stimulus consisted of pairs of increments, one to each eye. They are shown on the axes of Figure 6 as percentages of the standard increment. In short, the increment matching experiment was identical to the contrast-matching experiments except that luminance increments replaced sine-wave gratings.

These measurements help bridge the gap between the binocular contrast-matching measurements of this paper and the binocular brightness matching measurements of Levelt (1965). On the one hand, luminance increments may be regarded as stimuli having a very low spatial frequency (0 c/deg). On the other hand, Levelt's brightness matching experiments may be regarded as luminance-increment-matching experiments in which the background luminance was zero.

Figures 6a and 6b give data for Observers G.R. and A.W., respectively. For the largest standard increment, data are missing for A.W. at the extreme ratios because the luminance of the screen could not be increased sufficiently to obtain a match.

In Figure 6a, the closed circles, corresponding to increments of .2 cd/m², lie inside the quadratic summation curve, and the remaining two sets of data lie on it or outside it. For this observer, the smallest standard increment was matched by test pairs with the largest power summation index, the reverse of the contrast effect at 1 c/deg. This reversal, however, is not apparent in the data of A.W. (Figure 6b), for whom the magnitude of the standard increment had no consistent effect.

The luminance increment matching data of Figure 6 deviate systematically from binocular averaging. These data are somewhat better represented by quadratic summation. Apparently, under our conditions, luminance increment matching behaves more like binocular contrast matching than like binocular brightness matching. By comparison, Birch (1979) found that binocular averaging held for contrast matches at a low spatial frequency of .25 c/deg.

Fechner's Paradox

In a matching task, Fechner's paradox occurs when an increase in the intensity (either contrast or luminance increment) of one test component requires an increase in the intensity of the other test component to maintain a match between test and standard. In graphs such as Figures 3-7, Fechner's paradox occurs when the equal-contrast contour contains points lying upward and to the right of other points on the contour.

Fechner's paradox can be seen in Figure 4a where points near the horizontal axis lie up and to the right of points on the horizontal axis, for example, the solid circles with normalized contrasts of (0, 117) and (21, 130).

G.R. shows Fechner's paradox consistently for low left-eye contrasts at both 1 and 8 c/deg. It is less apparent for low right-eye contrasts at these spatial frequencies. D.K. shows a small effect for low right-eye contrasts at 8 c/deg. Evidence for the existence of a contrast version of Fechner's paradox is equivocal for other observers in other conditions. In any case, Fechner's paradox does not manifest itself as strongly in the present experiment as has been reported by Levelt (1965) for binocular brightness perception.

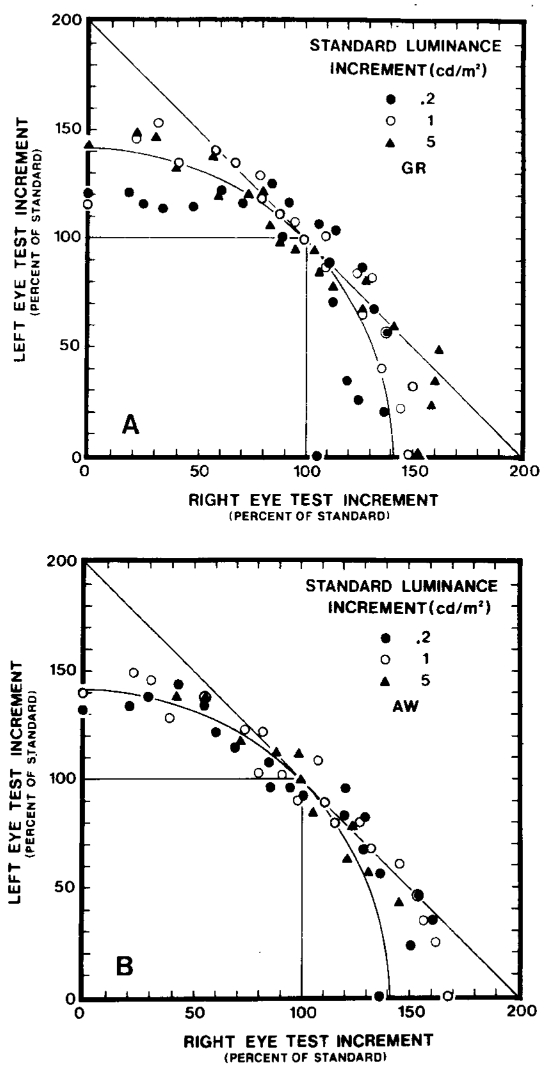

Figure 6. Binocular luminance increment matching functions. Stimuli were luminance increments added to the 10-cd/m² uniform fields. The standard increments were .2 cd/m² (●), 1 cd/m² (○), and 5 cd/m² (▲). Points are plotted as the right- and left-eye test increments whose binocular sum appeared to match the standard increment. Test increments are represented on the axes as percentages of the standard increment. Other details are as in Figure 4. (a) Observer G.R. (b) Observer A.W.

Ocular Dominance Effects

In the context of binocular contrast matching, we may operationally define ocular dominance as follows. Suppose we have a pair of test contrasts $C_1 > C_2$. We may present the greater test contrast, C_1, to either the right or the left eye. If the perceived binocular contrast is unaffected by which eye views the higher test contrast, we say there is no ocular dominance. If the perceived binocular contrast is consistently higher in the case in which the left eye is presented with the higher test contrast, we say there is left-eye ocular dominance. In the contrast-matching paradigm, ocular dominance is manifested as a reduction in the contrasts of the test components for a match when the high-contrast test component is presented to the dominant eye.

A good example of ocular dominance occurs in Figure 5b for a standard contrast of .1 (open circles). When the left eye's test contrast is low, rather high values of the right eye's test contrast are needed to match the standard. By comparison, when the right eye's test contrast is low, much lower left-eye test contrast is needed to match the standard. This asymmetry is manifested in Figure 5b as an apparent tilt of the open-circle data. Apparently, for this condition, Observer D.K.'s left eye dominates his right eye in the determination of perceived binocular contrast.

We observed rather wide individual differences in ocular dominance effects and varying degrees of ocular dominance for a given observer under different conditions. However, reversals in ocular dominance for a given observer did not occur. Figure 7 shows three sets of matching data illustrating different degrees of ocular dominance. All three sets of data were collected at 8 c/deg and at a standard contrast of .1.

G.R.'s data (closed circles) show slight ocular dominance in favor of the right eye. This ocular dominance was apparent for all standard contrasts at 8 c/deg (see Figure 5a), but did not occur for other spatial frequencies. D.K.'s data (open circles) are redrawn from Figure 5b. They show a rather strong ocular dominance in favor of the left eye. This pattern of ocular dominance occurred consistently across standard contrasts at 8 c/deg. It was also apparent in pilot data at 1 c/deg.

Levelt (1965) also reported ocular dominance in binocular brightness matches. He suggested that ocular dominance might reflect differences in sensitivity between the two eyes, but he could not verify such differences. Our measurements of monocular contrast thresholds revealed small differences in sensitivity consistent, in terms of direction, with the ocular dominance effects but unrelated to the magnitude of those effects. For example, M.A.'s data (triangles) show an enormous ocular dominance in favor of the left eye. In fact, M.A.'s binocular matches were virtually independent of the right eye's contrast until it was almost twice the standard contrast. This was the most extreme form of ocular dominance we observed. Yet, the difference in M.A.'s monocular contrast thresholds was smaller than G.R.'s, but G.R. showed much weaker ocular dominance. We could not relate M.A.'s extreme ocular dominance to any other property of his vision. M.A. showed very keen stereoacuity on an Orthorater stereoacuity test. We even measured M.A.'s accommodation with a binocular laser optom-

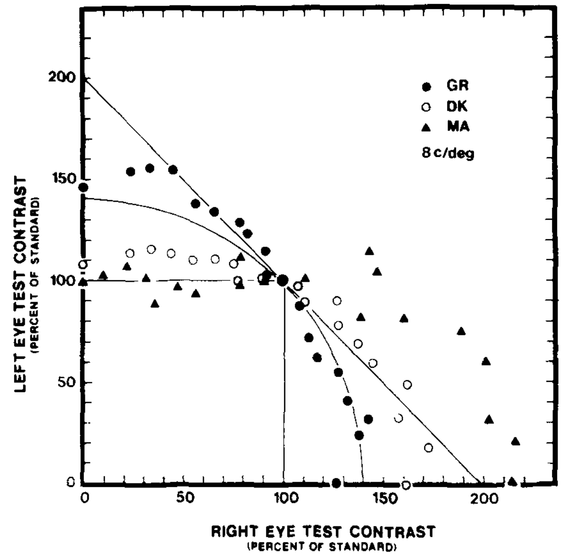

Figure 7. Binocular matching functions illustrating individual differences in ocular dominance. Binocular contrast matching functions are shown for three observers at 8 c/deg for a standard contrast of .1. G.R. (●) shows a slight ocular dominance in favor of the right eye. D.K. (○) shows substantial ocular dominance in favor of the left eye. M.A. (▲) shows an enormous ocular dominance in favor of the left eye.

eter for 8-c/deg stimuli, presented to him under the usual stimulus conditions. His accommodation was normal and did not differ significantly between the two eyes. M.A.'s pattern of ocular dominance was consistently found over several separate test sessions. The origin of this extreme form of ocular dominance remains a mystery.

Additivity Test

Additivity of monocular components in binocular contrast perception was examined by testing for violations of the monotonicity and cancellation rules. The monotonicity condition can be directly assessed by examining the contrast-matching curves in Figures 3-5. It is violated whenever an *increase* in the contrast of one test component requires an increase in the contrast of the other test component to maintain a match between test and standard. This is the case for Fechner's paradox. The evidence for Fechner's paradox has been reviewed earlier, showing that it does occur for some observers at various spatial frequencies and standard contrasts.

Table 2
Cancellation Test Results

		Fixed Contrasts				Adjusted Contrasts		
O	SF	L_2	R_2	R_1	R_3	L_1	L_3	L_4
G.R.	1	.10	.10	.040	.20	.1190	.2000	.2000
K.S.	1	.10	.10	.040	.20	.1080	.1940	.1940
G.R.	1	.01	.01	.004	.02	.0141	.0224	.0225
K.S.	1	.01	.01	.004	.02	.0140	.0216	.0224
G.R.	8	.10	.10	.040	.20	.1460	.2520	.2550
K.S.	8	.10	.10	.040	.20	.1520	.2570	.2420

Note—O = observer; SF = spatial frequency.

Our finding that Fechner's paradox occurs under some, if not all, contrast matching conditions indicates that the monotonicity condition is sometimes violated. Under these conditions, violations of the cancellation rule would also be expected. These expectations were confirmed in preliminary studies. However, monotonicity is obeyed over much of the range of the contrast-matching curves. Our tests of the cancellation rule were confined to this range. (For details of the cancellation test procedure, see Method section.) Data for each additivity test are shown in Table 2. Tests were conducted with 1- and 8-c/deg sine-wave gratings. For each step in the procedure, the observer adjusted the left-eye test contrast until test and standard binocular patterns matched in perceived contrast.[4] The median contrast for each step is shown in Table 2.

If binocular contrast perception is an additive process, $\hat{L}_3$ should equal $\hat{L}_4$. For two of the six cancellation tests, $\hat{L}_3$ and $\hat{L}_4$ are equal to three-figure accuracy. In the remaining four cases, the difference is not large enough ($p > .2$) to warrant rejection of the additivity hypothesis. For the conditions tested at 1 and 8 c/deg, we did not find a violation of additivity.

DISCUSSION

Models of Binocular Combination

We have used a power-summation rule to characterize our binocular contrast-matching results. This rule is an example of an additive form of binocular summation. The extent to which the exponent n deviates from a value of 1.0 is a measure of departure from linear addition (or averaging). For each of our sets of data, we found the value of n that yielded the best power summation fit.[5] In every case, n was greater than 1.0, indicating departures from linear addition. Values of n for Subject G.R., for whom we have the most complete data, are given in Table 3. As the results in Figures 3-7 and Table 3 indicate, n varies somewhat from subject to subject and across conditions, but a value of $n = 2$ is much more representative than a value of $n = 1$. We conclude, therefore, that for the conditions of our experiments, binocular contrast matching and luminance increment matching are more nearly described by quadratic summation than by linear summation or averaging.

Binocular quadratic summation suggests the presence of a "squaring" device in each monocular channel, prior to binocular combination. Square-law models are familiar from auditory psychophysics (see, e.g., Green & Swets, 1966) and have been used in models of vision as well (see, e.g., Rashbass, 1970).

Table 3
Best-Fitting Parameters of the Power Summation (n) and Vector Summation (α) Models for Observer G.R.

Spatial Frequency	Standard Contrast	n	α
1	.005	1.6	80
1	.010	1.6	78
1	.100	3.7	110
1	.500	4.3	113
8	.010	1.8	84
8	.100	1.8	85
8	.300	2.2	94
Luminance Increments			
	.200 cd/m²	3.2	107
	1	1.8	86
	5	1.6	76

Specifically, suppose that gratings seen by the left and right eyes have contrasts C_L and C_R, respectively. The outputs of the square-law mechanisms are $(C_L)^2$ and $(C_R)^2$. These outputs are added linearly to yield the binocular "signal,"[6] $(C_B)^2$:

$$(C_B)^2 = (C_L)^2 + (C_R)^2.$$

This simple model of binocular contrast summation can account for some rather diverse binocular contrast phenomena. First, quadratic summation gives a good first-order description of the binocular contrast-matching results of this paper. Second, this model accounts for the $\sqrt{2}$ relation between monocular and binocular contrast thresholds (Campbell & Green, 1965a); an increase in monocular grating contrast by a factor of $\sqrt{2}$ has the same effect on $(C_B)^2$ as presenting a second monocular grating of the same contrast to the contralateral eye. Third, the model predicts that dichoptic masking should elevate monocular contrast thresholds more than monocular masking, in keeping with the findings of Legge (1979). This property holds because the addition of a signal grating to a masking grating in the same eye elevates $(C_B)^2$ more than when the signal grating and masking grating are presented separately to the two eyes.

The binocular quadratic summation model is, of course, an oversimplification. It fails to predict the phenomena associated with Fechner's paradox and the deviations from exact quadratic summation. Two classes of interactive models—weighted summation (de Weert & Levelt, 1974; Engel, 1967, 1969, 1970; Levelt, 1965) and vector summation (Cohn & Lasley, 1976; Curtis & Rule, 1978)—have been applied to the problem of Fechner's paradox in binocular luminance summation.

In weighted summation models, binocular brightness, B_B, is a weighted sum of monocular brightnesses B_L and B_R:

$$(B_B)^k = (W_L B_L)^k + (W_R B_R)^k,$$

where W_L and W_R are weighting coefficients and k is a parameter similar to the power summation exponent. Each weighting coefficient depends on some property of the stimulation to both eyes, and possibly on an ocular dominance factor, thereby accounting for the interactive nature of these models. In one example of weighted summation, the centroid model (Schrodinger, 1926; de Weert & Levelt, 1974), weights are determined by the relative monocular target brightnesses and the parameter k is 1:

$$B_B = \left(\frac{B_L}{B_L + B_R}\right)B_L + \left(\frac{B_R}{B_L + B_R}\right)B_R.$$

We applied a weighted summation model to our contrast-matching data by substituting contrast for brightness in this equation.[7] Thus, the weighting coefficients for the centroid model of binocular contrast summation are the relative monocular contrasts. The weighted summation model gave its best performance in accounting for our high-contrast data at 1 c/deg. However, the interactive character of this model predicts violations of the cancellation rule even under conditions in which monotonicity obtains. We did not find violations of the cancellation rule, and the sensitivity of our additivity test was sufficient to detect the deviations predicted by the weighted summation model. Moreover, both the power summation and vector summation models (see below) provide better fits to the data than the weighted summation model, even in the region of its best performance. We conclude that the weighted summation model does not give a satisfactory account of binocular contrast combination.

Curtis and Rule (1978) have proposed vector summation as an alternative interactive model of binocular summation. Binocular brightness is the length of a vector that is the sum of two vectors having lengths B_L and B_R and an angle of α between them:

$$(B_B)^2 = (B_L)^2 + (B_R)^2 + 2\cos\alpha B_L B_R.$$

When the angle α is 0 deg, B_B is determined by the simple addition of monocular brightnesses. When α equals 90 deg, binocular brightness obeys a quadratic summation rule. More generally, as α increases from 0 deg, the model predicts matching functions, in the coordinates of Figures 3-7, that depart from the linear summation line and bend more rapidly towards the axes, intersecting at lower values. By appropriate choice of angle, this model can be made to fit data on the axes (i.e., zero brightness in one eye).

Curtis and Rule (1978) were able to fit binocular brightness data obtained from magnitude estimation experiments with a vector sum of monocular brightnesses having an angle of 113 deg. We applied the vector sum model to our contrast matching data by substituting contrast for brightness. When best-fitting values of the parameter α were chosen, the vector summation rule provided fits to our data with about the same RMS deviation as the best-fitting power summation rule. The values of α for Subject G.R. are given in Table 3. For standard contrasts of .1 and .5 at 1 c/deg, best-fitting values of α for G.R. were 110 and 113 deg, close to the values found by Curtis and Rule (1978). For other conditions, G.R.'s values of α were less.

Vector summation is an interactive model, and predicts that tests of additivity should reveal violations. However, when $\alpha = 90$ deg, vector summation is equivalent to quadratic summation, and additivity obtains. For values of α near 90 deg, the cancellation test predicts violations that are small, indeed. Even for $\alpha = 113$ deg, our estimates predict the difference between L_3 and L_4 to be less than 4%. This difference is too small to be detected reliably by our additivity test. Therefore, despite our failure to find violations of additivity, we do not rule out vector summation as a model of binocular contrast combination.

There is still the question of how to interpret the angle α in a model of suprathreshold binocular interaction. Cohn and Lasley (1976) have shown vector summation to be equivalent to the combination of information from summing and differencing mechanisms in binocular detection of luminance increments and decrements. In this case, the binocular detectability (d') of pairs of luminance changes was related to monocular detectabilities by a similar vector summation rule. The angle α was related to the relative contributions of the summing and differencing mechanisms in the detection process.

It seems plausible to propose the existence of "summing" and "differencing" mechanisms for the suprathreshold perception of contrast. Indeed, DeSilva and Bartley (1930) proposed such a pair of mechanisms to account for binocular brightness perception. Suppose that monocular contrasts C_L and C_R are combined in a "summing channel" whose output is $C_L + C_R$, and in a "differencing channel" whose output is $C_L - C_R$. Let binocular contrast C_B be a weighted quadratic sum of the outputs of these two channels so that:

$$(C_B)^2 = \frac{W_1}{W_1 + W_2}(C_L + C_R)^2 + \frac{W_2}{W_1 + W_2}(C_L - C_R)^2$$

$$= (C_L)^2 + (C_R)^2 + 2\left(\frac{W_1 - W_2}{W_1 + W_2}\right)C_L C_R.$$

Here, W_1 and W_2 are weighting coefficients that determine the relative contributions of the summing and differencing channels to the binocular percept. If we let $\cos\alpha = 2(W_1 - W_2)/(W_1 + W_2)$, we have a vector summation model for binocular contrast perception.

In summary, power summation rules and vector summation rules both provide satisfactory empirical fits to our contrast-matching data. The two models are equivalent when $\alpha = 90$ deg and $n = 2$. In this form, the two models provide a good consensus description of our data.

Conclusions

Our results lead us to the following conclusions.

(1) When either a 1- or a 8-c/deg sine-wave grating is presented with unequal contrast to the two eyes, the resulting binocular contrast percept is disproportionately dependent upon the high-contrast component. A similar result holds for small luminance increments superimposed on a 10-cd/m² uniform field. These findings indicate that binocular contrast summation does not obey a binocular averaging rule. Instead, binocular contrast summation more nearly obeys a quadratic summation rule.

(2) At 1 c/deg, the binocular contrast-matching functions deviate more from binocular averaging at high contrasts than at low contrasts. There is only a slight effect of contrast at 8 c/deg, and of increment size for the luminance-increment-matching data.

(3) We present evidence for a contrast version of Fechner's paradox which appears to be considerably weaker than its brightness counterpart.

(4) There are substantial individual differences in ocular dominance in contrast matching, just as there are for binocular brightness matching.

(5) When right and left eye contrasts are very different (Fechner's paradox region), an additive model of binocular summation seems inappropriate. In other cases, our results are consistent with additive models.

(6) Our binocular contrast matching data can be well fit by a power summation rule or by a vector summation rule.

REFERENCE NOTE

1. Chandler, J. P. STEPIT (*Quantum Chemistry Program Exchange*). Bloomington: Department of Chemistry, Indiana University, 1965.

REFERENCES

BACON, J. The interaction of dichoptically presented spatial gratings. *Vision Research*, 1976, **16**, 337-344.

BIRCH, E. E. Binocular processing of contrast: A vector sum model. *Supplement to Investigative Ophthalmology and Visual Science*, 1979, **18**, 246.

BLAKE, R. Threshold conditions for binocular rivalry. *Journal of Experimental Psychology: Human Perception and Performance*, 1977, **3**, 251-257.

BLAKE, R., & FOX, R. The psychophysical inquiry into binocular summation. *Perception & Psychophysics*, 1973, **14**, 161-185.

Blake, R., & Fox, R. Binocular rivalry suppression: Insensitive to spatial frequency and orientation change. *Vision Research*, 1974, **14**, 687-692.

Blake, R., & Levinson, E. Spatial properties of binocular neurones in the human visual system. *Experimental Brain Research*, 1977, **27**, 221-232.

Blake, R., Martens, W., & Di Gianfilippo, A. Reaction time as a measure of binocular interaction in human vision. *Investigative Ophthalmology and Visual Science*, 1980, **19**, 930-941.

Braccini, C., Gambardella, G., & Suetta, G. A noise masking experiment in grating perception at threshold: The implications of binocular summation. *Vision Research*, 1980, **20**, 373-376.

Campbell, F. W., & Green, D. G. Monocular versus binocular visual acuity. *Nature*, 1965, **208**, 191-192. (a)

Campbell, F. W., & Green, D. G. Optical and retinal factors affecting visual resolution. *Journal of Physiology* (London), 1965, **181**, 576-593. (b)

Cannon, M. W. Contrast sensation: A linear function of stimulus contrast. *Vision Research*, 1979, **19**, 1045-1052.

Cohn, T. E., & Lasley, D. J. Binocular vision: Two possible central interactions between signals from two eyes. *Science*, 1976, **192**, 561-563.

Curtis, D. W., & Rule, S. J. Binocular processing of brightness information: A vector sum model. *Journal of Experimental Psychology: Human Perception and Performance*, 1978, **4**, 132-143.

De Silva, H. R., & Bartley, S. H. Summation and subtraction of brightness in binocular perception. *British Journal of Psychology*, 1930, **20**, 240-250.

de Weert, C. M. M., & Levelt, W. J. M. Binocular brightness combinations: Additive and nonadditive aspects. *Perception & Psychophysics*, 1974, **15**, 551-562.

Engel, G. R. The visual processes underlying binocular brightness summation. *Vision Research*, 1967, **7**, 753-767.

Engel, G. R. The autocorrelation function and binocular brightness mixing. *Vision Research*, 1969, **9**, 1111-1130.

Engel, G. R. Tests of a model of binocular brightness. *Canadian Journal of Psychology*, 1970, **24**, 335-352.

Falmagne, J. C. Random conjoint measurement and loudness summation. *Psychological Review*, 1976, **83**, 65-79.

Fry, G. A., & Bartley, S. H. The brilliance of an object seen binocularly. *American Journal of Ophthalmology*, 1933, **16**, 687-693.

Gilliland, K., & Haines, R. F. Binocular summation and peripheral response time. *American Journal of Optometry and Physiological Optics*, 1975, **52**, 835-839.

Gottesman, J., Rubin, G. S., & Legge, G. E. A power law for perceived contrast in human vision. *Vision Research*, 1981, **21**, 791-799.

Green, D. M., & Swets, J. A. *Signal detection theory and psychophysics*. New York: Wiley, 1966.

Harwerth, R. S., Smith, E. L., III, & Levi, D. M. Suprathreshold binocular interactions for grating patterns. *Perception & Psychophysics*, 1980, **27**, 43-50.

Krantz, D. H., Luce, R. D., Suppes, P., & Tversky, A. *Foundations of measurement*. New York: Academic Press, 1971.

Legge, G. E. Spatial frequency masking in human vision: Binocular interactions. *Journal of the Optical Society of America*, 1979, **69**, 838-847.

Levelt, W. J. M. *On binocular rivalry*. The Hague: Mouton, 1965.

Levi, D. M., Harwerth, R. S., & Smith, E. L., III. Humans deprived of normal binocular vision have binocular interactions tuned to size and orientation. *Science*, 1979, **206**, 852-854.

Luce, R. D., & Tukey, J. W. Simultaneous conjoint measurement: A new type of fundamental measurement. *Journal of Mathematical Psychology*, 1964, **1**, 1-27.

Minucci, P. K., & Connors, M. M. Reaction time under three viewing conditions: Binocular, dominant eye and non-dominant eye. *Journal of Experimental Psychology*, 1964, **67**, 268-275.

Pirenne, M. H. Binocular and uniocular threshold of vision. *Nature*, 1943, **152**, 698-699.

Poffenberger, A. T. Reaction time to retinal stimulation with special reference to the time lost in conduction through nerve centers. *Archives of Psychology*, 1912, **23**, 1-73.

Rashbass, C. The visibility of transient changes in luminance. *Journal of Physiology* (London), 1970, **210**, 165-186.

Schrodinger, E. Die Gesichtsemfindungen. In *Muller-Pouillets Lehrbuch der Physik* (11 Auflage, Band 2:1). Braunschweig: Vieweg, 1926.

Sherrington, C. S. *The integrative action of the nervous system*. New Haven, Conn: Yale University Press, 1906.

Siegel, S. *Nonparametric methods for the behavioral sciences*. New York: McGraw-Hill, 1956.

Stevens, J. C. Brightness function: Binocular versus monocular stimulation. *Perception & Psychophysics*, 1967, **2**, 451-454.

Thorn, R., & Boynton, R. M. Human binocular summation at absolute threshold. *Vision Research*, 1974, **14**, 445-458.

NOTES

1. Fechner's paradox can be observed by viewing a bright field binocularly with a 1-log-unit neutral density filter over one eye. If the occluded eye is closed, the brightness of the field will increase, despite the fact that less energy is now impinging upon the visual system.

2. It is possible that the strength of dichoptic masking may be related to binocular rivalry. This is unlikely to be the case because dichoptic masking has orientation and spatial frequency selectivity unlike binocular rivalry (Blake, 1977; Blake & Fox, 1974). For a fuller discussion of this point, see Legge (1979).

3. When identical sine-wave gratings are presented to the two eyes but with unequal phase relative to the points of fixation, nonzero disparity is introduced. The observer perceives a sine-wave grating that lies in a depth plane other than the plane of fixation. We did not examine binocular contrast matching for gratings with nonzero disparities. It seems unlikely to us, however, that binocular contrast matches should vary with disparity.

4. Fixed contrast values for R_1 and R_3 were selected to ensure that the fixed test contrast did not exceed the adjustable test contrast during any step of the cancellation procedure. This restriction allowed the observer to match test and standard contrasts without the problems associated with shallow psychometric functions shown in Figure 2.

5. The best-fitting values of n (to the nearest .1) were found by minimizing the RMS deviation between data points in Figures 4-6 and curves predicted by the power summation rule with exponent n. Deviations were measured as distances along radii extending from the origin, since this is the direction along which errors in the test contrasts lie. The same procedure was used to find the best-fitting values of the parameter α (to the nearest 1 deg) in the vector summation model discussed below. The luminance increment matching data were fit by the same method, with luminance increments substituted for contrast in each model.

6. The binocular "signal," $(C_B)^2$, should not be equated with perceived binocular contrast. In order to account for contrast-magnitude-estimation data, and contrast-discrimination and masking data, we further require that $(C_B)^2$ be subjected to a nonlinear compressive transformation *after* the point of binocular combination.

7. We also evaluated the power summation, weighted summation, and vector summation models with *perceived contrast* substituted for brightness. Perceived contrast was assumed to be a threshold-corrected power function of stimulus contrast with exponent between .7 (Gottesman, Rubin, & Legge, 1981) and 1.0 (Cannon, 1979). The substitution did not improve the fit, but did change the values of n and α. Threshold correction reduced n and α for standard contrasts and luminance increments near threshold. A perceived contrast exponent of .7 rather than 1.0 increased best-fitting values of n and α.

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