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BINOCULAR CONTRAST SUMMATION—I. DETECTION AND DISCRIMINATION

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Abstract—Binocular summation was evaluated for contrast detection and discrimination. Monocular and binocular forced-choice psychometric functions were measured for the detection of 0.5-c/deg sine-wave gratings presented alone (simple detection), or superimposed on identical background gratings (discrimination). The dependence of detectability d' on signal contrast C could be described by: $d' = (C/C')^n$. C' is threshold contrast, and n is an index of the steepness of the psychometric function. n was near 2 for simple detection, near 1 for discrimination, and was approximately the same for monocular and binocular viewing. Monocular thresholds were about 1.5 times binocular thresholds for detection, but the ratio dropped for suprathreshold discrimination. These results reveal a dependence of binocular summation on background contrast. For simple detection, binocular detectabilities were at least twice monocular detectabilities. For contrast discrimination, the amount of binocular summation decreased. For a 25%-contrast background, there was little or no binocular summation. It is concluded that binocular contrast summation decreases as background contrast rises.

Binocular vision   Binocular summation   Contrast   Detection   Discrimination

INTRODUCTION

Binocular summation is a classic problem in vision. It is said to occur if a visual task which can be performed monocularly is performed more effectively binocularly. Binocular summation occurs in visual detection since two eyes are more effective at detecting stimuli than one under many conditions. Pirenne (1943) concluded that binocular summation at threshold was no more than would be expected if the stimulus were detected when it exceeded the threshold of either of two independent detectors. He termed this form of binocular summation *probability summation*. However, it has subsequently been shown conclusively that simultaneous stimulation of corresponding retinal points results in binocular summation in excess of probability summation (Thorn and Boynton, 1974). The many studies of binocular summation have been reviewed by Blake and Fox (1973) and Blake *et al.* (1981).

Binocular summation occurs for contrast detection. Campbell and Green (1965) showed that the monocular contrast thresholds for sine-wave gratings were about 1.4 times greater than the corresponding binocular contrast thresholds.

Typically, binocular summation in contrast detection has been evaluated in terms of differences in threshold contrast for monocular and binocular viewing. An alternate approach is to study performance differences for stimuli of fixed contrast, presented monocularly and binocularly. Performance can be indexed by percent correct in a detection task, or by the signal detection parameter d'. Threshold differences and performance differences can be obtained from measurements of psychometric functions (sometimes called frequency-of-seeing curves).

Figure 1 presents hypothetical psychometric functions obtained in a two-alternative forced-choice procedure. In Fig. 1(A), percent correct is plotted as a function of contrast (log scale) for monocular (M) and binocular (B) viewing. The horizontal dashed line at 75% correct intersects the two curves at contrasts yielding fixed levels of performance. By convention, these contrasts may be taken as threshold contrasts. The vertical dashed line in Fig. 1(A) intersects the two curves at different values of percent correct, indicating how performance differs for a fixed stimulus contrast. The size of this difference will depend on the contrast chosen. In Fig. 1(B), percent correct is transformed to d'. Log d' is plotted as a function of log contrast. In these coordinates, the psychometric functions are straight lines with slopes of 2. Typically, detection psychometric functions can be adequately represented by straight lines in log–log coordinates. Accordingly, they can be represented by equations of the form

$$d' = (C/C')^n. \tag{1}$$

Here, C is contrast. C' is a threshold parameter representing the contrast for which $d' = 1$ (corresponding to about 76% correct). The parameter n indicates the steepness of the psychometric function. For the curves in Figs 1(A) and 1(B), $n = 2$. $C' = 1$ for binocular viewing, and 1.41 for monocular viewing. When forced-choice data can be fit by straight lines in log d' vs log C coordinates, the parameters C'

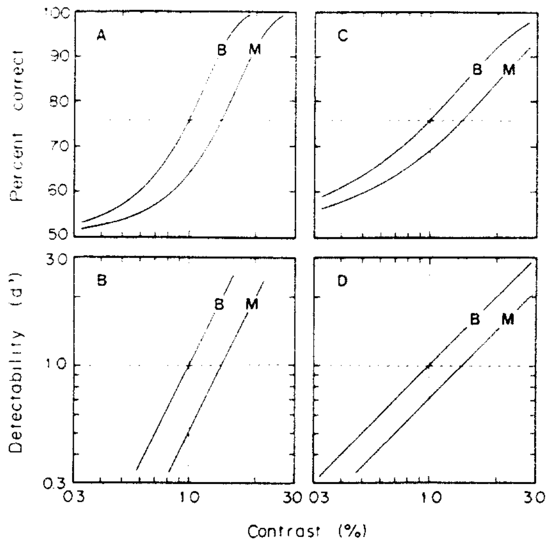

Fig. 1. Schematic psychometric functions for binocular (B) and monocular (M) viewing. The curves are derived from functions of the form given in equation (1). In panels (A) and (B), values of the threshold parameter C' and steepness parameter n are 1 and 2 for binocular viewing, and 1.41 and 2 for monocular viewing. In panels (C) and (D), C' and n are 1 and 1 for binocular viewing, and 1.41 and 1 for monocular viewing. In panels (A) and (C), the ordinate is percent correct for forced choice, as transformed from the d' ordinate values in panels (B) and (D).

and n are sufficient to characterize the curve. In panels (C) and (D) of Fig. 1, the psychometric functions are shallower, with $n = 1$. As in panels (A) and (B), the threshold parameters C' are 1, and 1.41 for binocular and monocular viewing respectively. In this case, the threshold difference (horizontal separation of curves) is the same as in panels A and B, but the performance difference (vertical separation between curves) is smaller.

Finally, in Fig. 1, the monocular and binocular psychometric functions have the same steepness parameter n. There is no *a priori* need for this equality. In fact, some models of binocular interaction, such as probability summation, predict unequal values of n for monocular and binocular viewing. If the values of n differ, the curves in Figs 1(B) and (D) would no longer be parallel. As a result, the ratio of binocular to monocular detectability would depend on stimulus contrast, and the threshold contrast ratio would depend crucially on the criterion level of performance chosen.

A major purpose of the current study was to measure and compare psychometric functions for monocular and binocular detection of sine-wave gratings. The psychometric functions permit binocular summation to be assessed not only in terms of threshold differences but also in terms of performance differences. In particular, the relation between binocular and monocular detectability can be assessed.

Foley and Legge (1981) measured binocular psychometric functions for the detection of 0.5, 2 and 8 c/deg sine-wave gratings. Their data were nicely fit by straight lines in log d' vs log C coordinates, with the steepness parameter n having values in the range 2 to 3. A power law relationship between d' and C with exponent greater than 1 has also been observed by Stromeyer and Klein (1974) and Nachmias and Sansbury (1974).

Not only do observers detect contrast, but they can be asked to discriminate between two patterns having contrasts of C and $C + \Delta C$. Here, C is the *background contrast* and ΔC is the *increment contrast*. How do two eyes compare with one in contrast discrimination? Is the contrast-increment threshold lower for binocular viewing than for monocular viewing? Once again, we can address these questions by examining threshold differences or performance differences. The full picture can be given by measuring psychometric functions for monocular and binocular contrast discrimination. In such measurements, percent correct is obtained as a function of increment ΔC, for a fixed background contrast C.

A second major objective of the current research was to measure psychometric functions for contrast discrimination, both monocularly and binocularly. Measurements were conducted for background contrasts of 1, 5 and 25%. Evidence already exists that psychometric functions for discrimination are markedly different than for detection (Nachmias and Sansbury, 1974; Foley and Legge, 1981), so it seemed probable that properties of binocular summation should also differ. This was found to be the case.

METHODS

Apparatus

Vertical sine-wave gratings were presented on a Joyce Electronics CRT display by Z-axis modulation. The display had a P31 phosphor, and mean photopic luminance of 340 cd/m^2 and a dark surround.

The contrast response of the CRT was measured with a UDT 80X Opto-Meter. Contrast is defined as $(L_{\max} - L_{\min})/(L_{\max} + L_{\min})$, where $L_{\max}$ and $L_{\min}$ are the maximum and minimum luminances in the sinusoidal luminance distribution. During the experiments, contrasts were kept within the CRT's linear range.

Split-screen viewing was arranged so that the left and right eyes could be stimulated with different patterns. A vertical, black septum extended from the center of the display to the observer's 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 septum. Trial lenses were selected so that the observer could comfortably converge and accommodate on the fixation marks. Observers were instructed to be sure that the nonius lines appeared to be in vertical alignment, and that the fixation dots were fused before initiating a trial.

Sine-wave voltages were produced by an LSI-11/2 computer and associated peripherals. Identical digital waveforms appeared at the outputs of two 12-bit D/A converters. These waveforms were passed through separate 9-bit programmable dB attenuators, then added, and then passed through an antialiasing filter before being applied to the Z-axis of the CRT. The waveform from one D/A served as the "background" sine-wave grating in the discrimination experiments, and the waveform from the other D/A acted as the "signal." With this arrangement, backgrounds and signals could be presented to either the right or left eye and the contrasts could be separately controlled with an accuracy of 1/4 dB. In addition, the computer sequenced trials, collected responses, and was used in analyzing the data.

Procedure

With one exception, all gratings were presented in cosine phase so that the fixation marks were centered on bright bars. In the "binocular 180°-phase" condition, a grating was presented in cosine phase to the left eye, and an identical grating was presented to the right eye, except that its phase was advanced through 180° so that the fixation mark was centered on a dark bar.

All experiments were conducted with 0.5-c/deg sine-wave gratings. This relatively low spatial frequency was chosen for two reasons. First, we wished to control the phase of the sine-wave patterns presented to the two eyes. Small vergence instabilities mean that it is difficult to specify phase for sinusoidal targets having spatial frequencies much higher than about 0.5 c/deg. Second, for convenience, we wished to use patterns having about equal contrast sensitivity in the two eyes. Small anisometropic differences are relatively less important at low spatial frequencies. We easily found observers with negligible differences in contrast sensitivity for their two eyes at 0.5 c/deg.

The viewing distance was 57 cm, and the half fields subtended 11° horizontally by 6° vertically.

A two-alternative forced-choice method was used to measure psychometric functions. A given experimental session was devoted to a background grating of fixed contrast—0 (simple detection), 1, 5 and 25% (discrimination). For each background grating, four to six signal gratings spanning a range of contrasts were selected. A forced-choice trial consisted of two 200 msec intervals separated by 600 msec. The background grating was gated on and off in both intervals. In each trial, one of the signal gratings was randomly selected, and added to the background grating in one of the two intervals. The observer indicated in which interval the signal occurred by pressing one of two keys. Feedback was provided. In the monocular conditions, stimuli were presented to only one eye within a trial, while the other eye viewed a uniform field (apart from fixation marks and dark surround) of the same mean luminance. In the binocular conditions, identical stimuli were presented to both eyes. For all experiments in which monocular and binocular comparisons were to be made, monocular and binocular trials were randomly interleaved.* In addition, both right-eye and left-eye monocular trials were usually interleaved. A typical 1 to 2-hr experiment consisted of 1200 trials in which 5 four-contrast psychometric functions were obtained, each curve based on about 240 trials.

Data analysis

The raw data consisted of the numbers of trials and the percentages correct for a set of signal contrasts added to a given background grating. The data were fit by functions of the form given in equation (1). Maximum-likelihood estimates were found for the threshold parameter C' and the steepness parameter n of the psychometric function. χ^2 tests indicated that functions of the form given in equation (1) almost invariably provided reasonable fits to the data. Four to seven sessions were conducted for each observer in each condition, providing four to seven estimates of C' and n. Monte Carlo simulations (based on binomial error only) indicated that estimates of C' and n were distributed in approximately log-normal fashion. Hence, geometric means of C' and n were taken as estimates of threshold and slope. The variability of the slope parameter estimates was much greater than the variability of threshold estimates.

Observers

Six observers, all in their 20's, participated in the experiments. None showed significant eye differences in their contrast thresholds for 0.5 c/deg gratings. All observers had normal colour vision, and normal stereopsis.

RESULTS

Detection

In the detection experiments, the grating appeared in one of the two intervals of the forced-choice trial. In the monocular case the grating was presented to one eye, and in the binocular case, identical gratings were presented to both eyes. By interleaving trials in which several grating contrasts were used, psychometric functions were compiled.

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*In some experiments, "dichoptic discrimination" trials were also interleaved, in which the background and signal gratings were presented to different eyes. The dichoptic results will be discussed in the accompanying paper (Legge, 1984).

Figure 2(A) presents psychometric functions from four sessions for observer D.P. Percent correct, ranging from 50 to 100%, is plotted as a function of grating contrast (log scale). Open symbols refer to left-eye (monocular) signals and solid symbols to binocular signals. (Right-eye data were collected in the same sessions, but are not shown in Fig. 2.) Corresponding open and solid symbols refer to data obtained in the same session. For example, open and solid circles represent data collected in session D.P.8. Each symbol is based on 40–50 trials, so the four symbols in a set constitute a psychometric function based on about 200 trials.

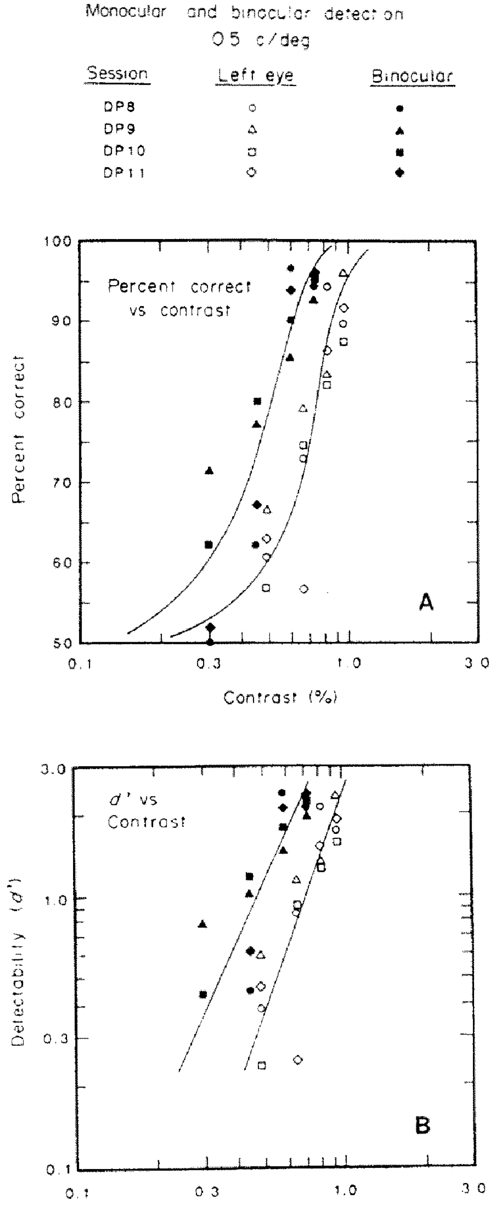

Fig. 2. Psychometric functions for 0.5-c/deg grating detection. Monocular and binocular psychometric functions, collected in four sessions from observer D.P., are shown. Each symbol is based on 40–50 forced-choice trials. Corresponding monocular and binocular symbols are based on trials that were interleaved within a single observing session. In panel (A), percent correct is plotted as a function of contrast. In panel (B), the data are replotted as detectability d' as a function of contrast. The straight lines through the data in panel (B) are maximum-likelihood fits to the monocular and binocular data (see text). The sigmoids through the data in panel (A) are transformed versions of the straight lines in panel B.

The data of Fig. 2(A) are replotted in 2(B) as detectability d' vs contrast—both on log scales. d' for forced-choice is computed as $\sqrt{2}$ times the normal deviate (Z-score) corresponding to percent correct (Green and Swets, 1974). [For binocular detection, d' values for signal contrast of 0.3 fall off the scale of Fig. 2(B) for D.P.8 and D.P.11.] The solid curves through the data in Fig. 2(B) represent equations of the form given in equation (1). The curves are characterized by a threshold parameter C' and a steepness parameter (or slope) n. For the left-eye data in Fig. 2(B), mean C' is 0.72% and mean n is 2.69. For the binocular data, C' is 0.48% and n is 2.18. For these data, the left-eye monocular threshold is 1.5 times greater than the binocular threshold, and both the monocular and binocular psychometric functions can be described by power law relations between d' and contrast with exponents greater than 2. In general, straight lines provide adequate fits to the measured psychometric functions in log–log plots of d' vs contrast. The sigmoidal solid curves through the data in Fig. 2(A) are transformed versions of the straight lines in Fig. 2(B).

Figure 3 shows left eye, right eye, and binocular data for observer D.P., pooled across four sessions. As a result, each symbol represents about 200 trials, and each psychometric function is based on approximately 800 trials. In Fig. 3(A), data are plotted as percent correct vs contrast, and in Fig. 3(B) as d' vs contrast. Unlike Fig. 2(B), however, the d' axis in Fig. 3(B) is linear. The linear scale was chosen to facilitate discussion of additivity (see below).

D.P.'s mean monocular contrast thresholds, estimated from four psychometric functions (see Method), were virtually identical—0.72 and 0.725% for right eye and left eye respectively. The corresponding slopes were 2.64 and 2.69. Although interocular threshold and slope differences were usually greater than these for other observers and conditions, no significant differences were found (t-test, $P < 0.05$).

When D.P.'s monocular data were pooled, the ratio of mean monocular threshold to mean binocular threshold was 1.5, the mean monocular slope was 2.66, and the mean binocular slope was 2.18. These values appear in Table 1. The entire experiment was replicated on observer D.P. in six additional sessions. The results were similar. As indicated in the second column in Table 1, the monocular/binocular threshold ratio in the replication was 1.53, the mean monocular slope was 1.83, and the mean binocular slope (in-phase condition) was 1.99.

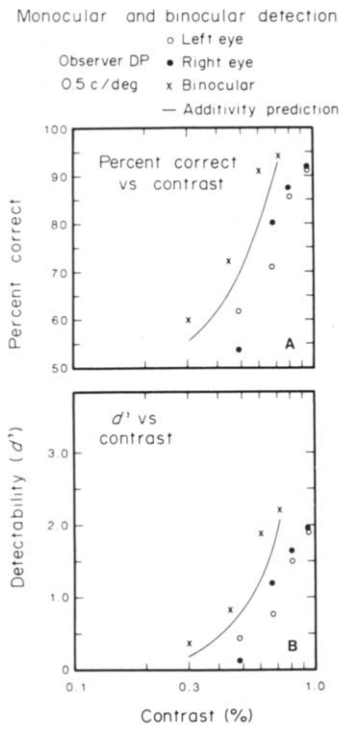

Fig. 3. Monocular and binocular detection psychometric functions. Left eye, right eye, and binocular psychometric functions for the detection of 0.5-c/deg gratings are shown for observer D.P. Points are based on data pooled across four sessions, and represent about 200 forced-choice trials. In panel (A), percent correct is plotted as a function of contrast. In panel (B), data are replotted as d' vs contrast, with a linear ordinate. The solid curve represents binocular performance to be expected if binocular detectability is equal to the sum of the monocular detectabilities.

The same experiment was conducted with observers K.B. and K.J. Their results are summarized by threshold ratios and slopes in Table 1.

The parameter estimates in Table 1 indicate the following concerning psychometric functions for monocular and binocular contrast detection. (i) The monocular/binocular threshold ratio is close to 1.5, and appears to be slightly greater than the value of $\sqrt{2}$ associated with some models of binocular combination. (ii) The slopes of the monocular and binocular psychometric functions have values near 2 or perhaps a little more. The results of this and other experiments suggest that the average value is a little greater than 2. Precision in estimates of the slope is hard to achieve. (iii) For the four cases in which monocular and binocular slopes could be compared, no significant differences were found by t-test. (K.B.'s monocular slope estimate of 1.52 had a large standard error of 42%.) Within the resolution of these measurements, it may be concluded that monocular and binocular psychometric functions for contrast detection have the same shape, but differ by a contrast scale factor of 1.5.

For three observers, psychometric functions were measured for binocular detection in which the gratings presented to the two eyes were 180° out of phase. Threshold ratios and slopes are given in Table 1. The monocular/binocular threshold ratio dropped to about 1.3, indicating that the 180°-phase binocular stimulus was less detectable than the in-phase binocular stimulus, but still more detectable than the monocular stimuli.

Monocular and binocular psychometric functions may be used in two ways to evaluate binocular

Table 1. Threshold ratios[a] and slopes[b]

	Observers						
	D.P.	D.P.	K.B.	K.J.	G.D.	C.S.	W.W.L.
Detection							
Threshold ratio							
in-phase	1.50	1.53	1.64	1.51			
180°-phase	1.30	1.34	1.26				
Slope							
monocular	2.66	1.83	1.52	2.10		2.00	
binocular							
in-phase	2.18	1.99	2.48	2.63			
180°-phase	2.53	2.44	3.75				
Discrimination (1% contrast)							
Threshold ratio	1.60			1.27	1.54		
Slope							
monocular	1.26			1.09	1.28		
binocular	0.74			0.93	0.67		
Discrimination (5% contrast)							
Threshold ratio	1.54	0.83	1.20			1.28	1.37
Slope							
monocular	0.92	0.76	0.83			0.77	0.76
binocular	0.52	1.11	0.76			0.80	0.55
Discrimination (25% contrast)							
Threshold ratio	1.01		1.14	0.96			
Slope							
monocular	0.67		0.99	0.78			
binocular	1.04		0.62	1.12			

[a] Ratio of monocular to binocular contrasts at threshold.
[b] Exponent n in the relation, $d' = (C/C')^n$.

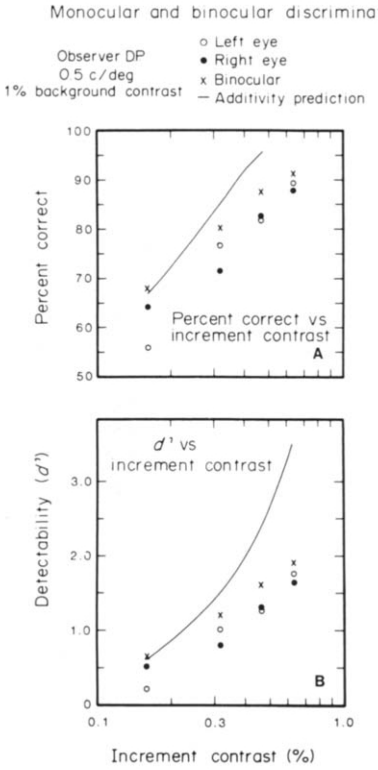

Fig. 4. Monocular and binocular discrimination psychometric functions. The observer attempted to detect contrast increments (abscissa) added to a 1% background grating. Other details as in Fig. 3.

summation. First, the threshold ratios of Table 1 indicate that a grating's contrast must be increased by about 50% if performance is to remain constant when the observer uses one eye rather than two. But, how does performance differ for monocular and binocular viewing of a grating with fixed contrast? To answer this question, we can compare monocular and binocular values of d' for a given contrast. "Simple d' summation" (Green and Swets, 1974) is said to occur if the binocular detectability is equal to the sum of the left- and right-eye monocular detectabilities. In symbols, simple d' summation occurs if

$$d'_B = d'_L + d'_R. \qquad (2)$$

As an empirical benchmark, we will refer to the case of simple d' summation as *full summation*. When binocular detectability falls short of full summation but is greater than monocular detectability, *partial summation* is said to occur. When binocular detectability is greater than full summation, *facilitation* is said to occur. As described by Legge (1984), equation (2) is predicted by a binocular-summation model based on the energy detector.

In Fig. 3(B), the solid curve represents the sum of monocular detectabilities. On the linear d' scale, the solid curve lies at approximately the sum of the heights of the left-eye and right-eye data points. (The addition is not exact because the solid line was derived from best-fitting curves through the two monocular data sets, rather than from pairs of points.) The solid curve in Fig. 3(A) is the transformed version of the solid curve in Fig. 3(B). In Fig. 3, the X's represent binocular performance. The X's all lie above the solid curve. This means that binocular detectability is greater than the sum of the monocular detectabilities, and suggests *facilitation*. In the other three binocular in-phase detection experiments, the results were similar, but with closer adherence to simple d' summation and less evidence of facilitation.

We may index the binocular summation of detectabilities by a *summation ratio*. The summation ratio is defined to be the ratio of binocular to monocular detectability for a contrast that yields a binocular d' value of 1. To the extent that binocular and monocular psychometric functions have identical slopes, the summation ratio will be independent of the contrast. (In this case, the summation ratio can be computed as the threshold ratio raised to the power n, where n is the steepness parameter.) Full summation is represented by a summation ratio of 2. In Fig. 7, the summation ratio is plotted for detection and discrimination experiments. The horizontal axis is background contrast. For detection, the background contrast is 0. The four detection experiments all have summation ratios greater than 2. However, for none of the four experiments did χ^2 goodness-of-fit tests on the binocular proportions reject the hypothesis that binocular detectability is equal to the sum of monocular detectabilities (0.05 criterion). It may therefore be concluded that using two eyes approximately doubles the detectability achieved by using just one eye, with the possibility of a weak facilitation effect in addition.

Discrimination

In the discrimination experiments, gratings of contrast C and $C + \Delta C$ were presented in the two intervals of the forced-choice trial. The observer was required to identify the interval with the higher contrast. Throughout a session, the background contrast C was fixed. However, a set of values of increment contrast ΔC were randomly sampled in order to compile a psychometric function for increment detection. In the monocular trials, gratings were presented to only one eye while in the binocular trials, identical gratings were presented to both eyes. Experiments were conducted with background contrasts of 1, 5 and 25%.

Figure 4 presents psychometric functions for detection of increment contrasts added to a background of 1% contrast. The symbols represent data pooled across five sessions for observer D.P. Each point is based on approximately 250 trials, so each psychometric function is based on about 1000 trials. In Fig. 4(A), percent correct is plotted as a function of

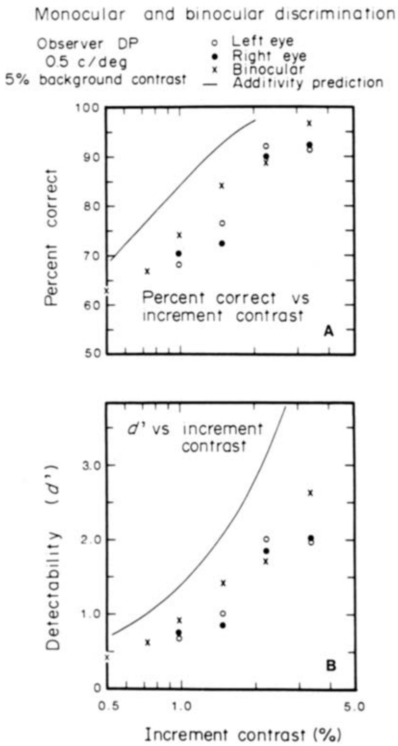

Fig. 5. Monocular and binocular discrimination psychometric functions. The observer attempted to detect a contrast increment (abscissa) added to a 5%-contrast background grating. Other details as in Fig. 3.

increment contrast for left eye, right eye, and binocular viewing. The data are replotted in Fig. 4(B) with d' as the ordinate. The solid curves represent the additivity prediction, that is, the sum of monocular detectabilities.

The mean monocular and binocular thresholds for D.P. were 0.40 and 0.25% respectively. Notice that these values are lower than the corresponding detection thresholds. The fact that near-threshold discrimination can be better than detection has been studied by several investigators, including Nachmias and Sansbury (1974) and Foley and Legge (1981). The monocular/binocular threshold ratio for D.P. is 1.60. Similar experiments on observers K.J. and G.D. yielded threshold ratios of 1.27 and 1.54 (Table 1). These values are not very different from the threshold ratios obtained for detection. However, comparison of Figs. 3 and 4 makes evident an important distinction between detection and discrimination. The psychometric functions for discrimination are shallower. In Fig. 4, D.P.'s mean monocular slope is 1.26, and her binocular slope is 0.74, both values being closer to 1 than 2. Examination of Table 1 shows that similar results obtained for observers K.J. and G.D. From the Table, discrimination with 1%-contrast backgrounds appears to be the only case for which monocular and binocular slopes are systematically different, with monocular slopes being slightly higher.

In Fig. 4, the binocular data, X's, clearly lie above the monocular data, indicating a binocular summation effect. However, the X's lie on or below the line representing the additivity prediction. Apparently, in the case of near-threshold increment detection, binocular summation of detectabilities is only partial.

In Fig. 7, the summation ratios for the three subjects who participated in the near-threshold discrimination experiment are plotted at an abscissa value of 1. Notice that the values lie between summation ratios of 1 and 2, indicating partial summation, with none achieving full summation.

Inspection of Table 1 shows that the threshold ratios are not very different for detection and for near-threshold discrimination. Measurements of threshold alone might suggest that binocular summation is the same in the two cases. However, because the slopes of the psychometric functions are smaller for discrimination, the difference in monocular and binocular performance for a given incremental signal contrast is less than in the case of detection. The situation for near-threshold discrimination is very much as schematized in Fig. 1(C) and (D).

Figure 5 shows more discrimination data for observer D.P., this time for a background contrast of 5%. Again, the solid curves represent predictions of simple d' additivity. The binocular data, X's, lie above the monocular data, but not by much. There is a small binocular advantage, but much less than predicted by additivity.

The threshold ratios and slopes for this experiment are listed in the first column of Table 1. Corresponding parameters from a replication of the experiment by observer D.P. and for experiments with three other observers are also listed. The threshold ratios lie in the range from 0.83 to 1.5, with a value of 1.25 being representative. Apparently, the monocular contrast discrimination threshold is slightly higher than the binocular one for a 5%-contrast background. From the Table, it can be seen that the monocular and binocular slopes are comparable, and seem to be slightly less than 1.

The decreased threshold ratio and relatively low slopes combine to yield low values of the summation ratio. The summation ratios for the five experiments are plotted at an abscissa value of 5 in Fig. 7. From these results, it is clear that the binocular advantage for discrimination against a 5%-contrast background is small, whether measured in terms of thresholds or detectabilities.

Finally, Fig. 6 shows psychometric functions for discrimination when the background contrast is 25%, for observer D.P. This time, the binocular data overlap the monocular data. There is no clear evidence for any binocular advantage. In Table 1, threshold ratios and slopes are listed for D.P. and two other observers. The threshold ratios are close to 1, indicating no difference between monocular and bin-

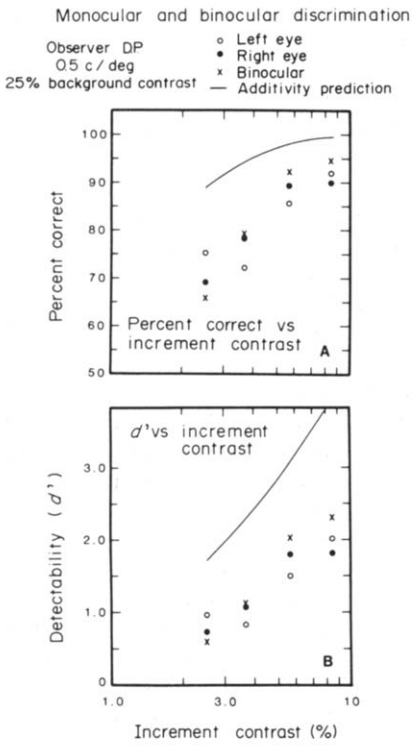

Fig. 6. Monocular and binocular discrimination psychometric functions. The observer attempted to detect a contrast increment added to a 25%-contrast background grating. Other details as in Fig. 3.

ocular increment thresholds. The monocular and binocular slopes again lie close to 1. The symbols plotted at the abscissa value of 25 in Fig. 7 show the summation ratios for contrast discrimination at 25% contrast. All the ratios are close to 1, indicating no summation. At least for these three observers, there was no binocular advantage in performing this discrimination task.

DISCUSSION

The results are summarized in Fig. 7 in which the summation ratio is plotted as a function of background contrast. When the background contrast is 0, we have simple detection. Nonzero background contrasts refer to contrast discrimination. When the summation ratio is 1, there is no binocular summation, and monocular and binocular thresholds are about equal. When the summation ratio is 2, there is full binocular summation, and the binocular detectability is about equal to the sum of the monocular detectabilities. When the summation ratio is greater than two, we have facilitation, and binocular detectability exceeds the sum of the monocular detectabilities. In Fig. 7, it is evident that binocular summation associated with the detection of 0.5-c/deg sine-wave gratings is equivalent to or greater than full summation. However, for discrimination, the amount of binocular summation decreases steadily with increasing background contrast (confirmed by a significant effect of background contrast on values of the summation ratio in an analysis of variance. $P < 0.01$). For the near-threshold background of 1% contrast, there is partial summation of detectabilities. For the suprathreshold background contrasts of 5 and 25%, there is very little binocular summation. Apparently, the substantial binocular advantage that exists for detection is markedly reduced for discrimination.

Decreased summation effects in contrast discrimination have been noted in other contexts. Legge and Foley (1980) found less spatial summation in contrast discrimination than in contrast detection. When they increased the number of sine-wave grating cycles from 1.5 to 12, there was a substantial drop in detection threshold, but very little effect on suprathreshold contrast discrimination. Similarly, Legge and Kersten (1983) observed that temporal duration had a much greater effect on detection thresholds than high contrast discrimination thresholds for light and dark luminous bars viewed against a uniform field.

The monocular and binocular psychometric functions have been characterized by threshold and slope parameters, equation (1). These parameters are summarized in Table 1 for the various conditions as monocular/binocular threshold ratios and monocular and binocular slopes. The threshold ratios are about 1.5 for detection, but appear to drop towards 1 for

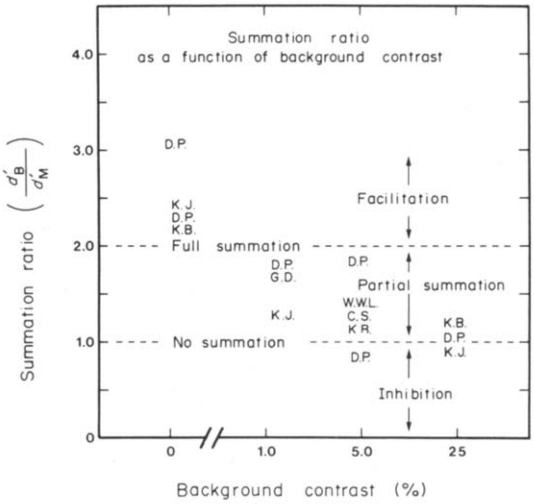

Fig. 7. Binocular summation ratio. Binocular summation for contrast detection and discrimination is summarized for several experiments. The summation ratio is defined as the ratio of binocular detectability to average monocular detectability, d'_B/d'_M, for a binocular detectability of 1. The abscissa represents background contrast. The abscissa value of 0 corresponds to simple detection. Each set of initials represents the summation ratio for one observer in one experiment. Some replications for observer D.P. are shown. The results indicate that binocular summation is much greater for contrast detection than for suprathreshold contrast discrimination.

discrimination as background contrast rises. The slopes which appear to be near 2 for detection drop quickly to values at or below 1 for discrimination. Both the drop in threshold ratio and the drop in slope contribute to the decrease in summation ratio evident in Fig. 7.

Some models of binocular combination, such as probability summation, predict psychometric functions with unequal slopes for monocular and binocular viewing. With the exception of contrast discrimination with 1%-contrast backgrounds, the slope estimates in Table 1 indicate no clear difference between monocular and binocular viewing. For the case of 1% backgrounds, the monocular slopes appear to be a little larger than the binocular slopes. Perhaps this difference occurs because "effective" background contrast is slightly lower in monocular viewing than in binocular viewing. For very low background contrasts, we would expect slopes to rise to values near 2 which are characteristic of detection.

Kristofferson (cited in Green and Swets, 1974) measured psychometric functions for monocular and binocular detection of light flashes with no background in peripheral retina and in the fovea (with a 10 ft-L background). In both cases, his data were similar to the detection data of this paper. The binocular d' was approximately equal to the sum of the monocular d' values. Data of Bacon (1976) suggest that, for at least one contrast, binocular detectability was more than twice the monocular detectability for 5.0-c/deg sine-wave gratings. Recently, Cogan *et al.* (1982) have measured monocular and binocular psychometric functions for the detection of "contrast flashes" (LED's flashed on uniform backgrounds). They fit their psychometric functions with straight lines in linear coordinates, thereby characterizing their data by slope parameters of 1. However, they found that the ratio of binocular to monocular detectability, d'_B/d'_M, was greater than 2 for low d' values and less than 2 for high d' values. This change in summation ratio implies that their binocular psychometric functions were shallower than their monocular psychometric functions. Indeed, a reanalysis of their Fig. 4 yielded slope parameters of about 2 and 3 for their two monocular psychometric functions, and a slope of about 1.1 for their binocular psychometric function. Apparently, the binocular functions were shallower than the monocular counterparts for their other observers as well. Evidence presented in the present paper indicates no clear difference between monocular and binocular slopes for grating detection. Values of the binocular slopes found in this study, and in studies cited earlier, appear to be nearer 2 than 1. Reasons for the lower binocular slopes found by Cogan *et al.* are not apparent.

The results of the present study confirm previous studies in showing that 180°-phase binocular gratings are less detectable than in-phase binocular gratings, but more detectable than monocular gratings (Blakemore and Hague, 1972; Bacon, 1976; Green and Blake, 1981). The monocular/binocular threshold ratios given in Table 1 for 180°-phase binocular detection average 1.30. This is exactly what would be expected according to a simple model of probability summation (see below) if the participating monocular detectors have psychometric functions with slopes of 2. However, this model also predicts that the binocular slope will be less than the monocular slope. This result was not obtained for the detection of the 180°-phase binocular gratings (see Table 1). For this reason, it cannot be concluded that probability summation gives a fully adequate description of the 180°-phase binocular detection data of this paper. On the basis of empirical measures of probability summation, Green and Blake (1981) concluded that thresholds for 180°-phase binocular gratings conform to probability summation predictions. It is interesting to note that a parallel finding exists for fused, luminous increments. The detection threshold is higher for an increment presented to one eye and a decrement to the other than for increments (or decrements) presented to both eyes. Each of these binocular combinations has a lower threshold than monocular increments or decrements (Westendorf and Fox, 1974; Cohn and Lasley, 1976). Westendorf and Fox (1974) have shown that the increment–decrement detectability is predicted from empirical measures of probability summation. Cohn and Lasley (1976) have argued that increment–decrement pairs are detected by a different mechanism (presumably less sensitive) than the mechanism that detects increment–increment binocular stimuli.

The experiments of this paper were conducted with 0.5-c/deg gratings. What effects might spatial frequency have? Monocular and binocular thresholds have been obtained over a range of spatial frequencies in several studies, but comparable data for discrimination are not available. Neither Campbell and Green (1965) nor Blake and Levinson (1977) found any systematic effect of spatial frequency on the monocular/binocular threshold ratio. Rubin (1983), using methods similar to those of this paper, has made limited measurements of monocular and binocular psychometric functions for the detection of gratings having spatial frequencies of 0.25, 1, 2 and 6 c/deg. In all cases, monocular and binocular slopes were similar, and tended to be greater than 2. His monocular/binocular threshold ratios lie in the range 1.3–1.7. His results show no systematic effects of spatial frequency, and suggest that properties of binocular summation may be similar across a broad range of spatial frequencies. On the other hand, both Rose (1978) and Arditi *et al.* (1981) have presented evidence that the monocular/binocular threshold ratio may depend on spatial frequency for drifting or flickering gratings.

The results of this paper impose constraints on models of binocular combination. Evidence has already accumulated that binocular summation for detection exceeds probability summation. The detection data of this paper provide further confirmation. The probability summation model holds that in binocular viewing, the two eyes act as independent detectors, each with a threshold. The stimulus is detected if either one or both thresholds is exceeded. If neither monocular threshold is exceeded when the stimulus is presented in a forced-choice trial, the observer is assumed to guess. Assuming equal sensitivities for the two eyes, probability summation predicts the following relation between monocular proportion correct P_M and binocular proportion correct P_B for two-alternative forced choice

$$P_B = 1 - 2(1 - P_M)^2. \tag{3}$$

[This formula is equivalent to one given by Blake and Fox (1973) in their Appendix A.] This probability summation model relates monocular and binocular probabilities, or equivalently, d' values. It says nothing about the relation between d' and contrast for monocular viewing. If we assume that d' is proportional to squared contrast for monocular detection, application of equation (3) predicts a monocular/binocular threshold ratio of about 1.3 and a binocular slope of about 1.75. Both of these predicted values are lower than the parameter estimates given in Table 1.

Can probability summation account for the discrimination data? Assume that d' is proportional to increment contrast for monocular discrimination. Applying equation (3), it can be shown that probability summation predicts a threshold ratio of 1.75 and a binocular slope of about 0.95. 1.75 is higher than any of the threshold ratios measured for discrimination and listed in Table 1. Apparently, probability summation does not describe the differences between monocular and binocular contrast discrimination.

According to signal detection theory, the optimal rule for combining information from two independent detectors has the following form

$$d'_{\text{total}} = \sqrt{(d'_1)^2 + (d'_2)^2}. \tag{4}$$

If monocular detectabilities are assumed to be equal, this rule predicts that $d'_B = \sqrt{2}d'_M$. For the case of detection, this model predicts a summation ratio (Fig. 7) of $d'_B/d'_M = \sqrt{2} = 1.41$. Moreover, if d' is proportional to squared contrast for detection, this model predicts a threshold ratio of $2^{1/4} = 1.19$. These predicted values are not in accord with the results of this paper.

In Fig. 7, the summation ratios are close to 2 for detection and close to 1 for high-contrast discrimination. How do these values compare with maximum and minimum values that might be expected on general grounds? One way to establish an upper bound on binocular summation is to compute improvement in performance to be expected from a doubling of monocular contrast. If we assume that for detection, monocular d' is proportional to squared contrast, a doubling of monocular contrast will result in a quadrupling of d'. Instead of doubling the contrast to one eye, we may present the same contrast to both eyes. This results in only a doubling of d', i.e. simple d' summation. Although simple d' summation has been termed *full summation*, it falls well short of the upper bound. The fact that the binocular summation ratio is close to 2 rather than 4 suggests that the locus of binocular combination *follows* the process that accounts for the square-law behaviour of the detection psychometric function.

Probability summation is sometimes thought to impose a lower bound on binocular summation. It may therefore seem surprising that the summation ratio for high-contrast discrimination is close to 1, indicating no binocular summation at all. Paradoxically, this implies that two cooperating individuals, each looking with one eye, would likely do a better job at discriminating contrasts than one individual looking with two eyes. This can be understood by realizing that a relaxation of the independence assumption of probability summation need not result in improved binocular summation. For example, if the internal noise processes that limit performance in the separate monocular channels of the probability summation model become correlated at suprathreshold contrasts, the extent of binocular summation will decrease.

In contrast to models in which the monocular channels remain independent until a decision is made, models of binocular summation can be formulated in which monocular signals are combined in some manner to form a "binocular signal." The observer's decision is based on some property of the binocular signal. Recent models of this sort include those of Cohn and Lasley (1976) and Cogan (1982). Legge (1984) describes a model of this sort called "quadratic summation." It is closely related to the *energy detector* model of signal detection theory (Green and Swets, 1974). According to the quadratic summation model, the "effective binocular contrast" C_B is related to left and right monocular contrasts C_L and C_R by the quadratic relation

$$C_B = \sqrt{(C_L)^2 + (C_R)^2}. \tag{5}$$

It will be shown that this combination rule gives a good, first-order account of many of the results of this paper, as well as a number of other phenomena of binocular contrast interaction.

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