Disparity Range For Binocular Summation

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Binocular summation of contrast and stereopsis have been linked because they both disappear under certain pathological conditions. The dependence of stereopsis on spatial frequency prompted us to examine how binocular summation varies with both spatial frequency and binocular disparity. We therefore measured binocular summation at different disparities using spatially localized stimuli which were also restricted in their Fourier composition. Contrast thresholds were measured using three interleaved forced-choice staircases for left and right eye monocular stimuli and a binocular stimulus composed of the two monocular stimuli presented simultaneously. At zero disparity binocular thresholds were 1.4 to 1.6 times lower than monocular. As disparity was increased the ratio between the thresholds became smaller, such that at large disparities it was near 1.2, the value expected from probability summation. The range of disparities over which probability summation was exceeded varied with the spatial frequency of the stimulus. At 6.0 cpd the range was 2–3 deg, but at 2.0 cpd or 0.75 cpd the range increased to 4–6 deg. These values closely parallel the range of disparities over which stereoscopic depth sensations occur, but they exceed the limits within which disparate images of an object can be fused into a single percept. The results support the contentions that “neural” summation occurs in the mechanism for stereopsis, that this mechanism uses spatial frequency selective channels, and that this mechanism is separate from the mechanism which mediates fusion. Invest Ophthalmol Vis Sci 29:283–290, 1988

Two eyes are better than one on a variety of threshold and suprathreshold visual tasks.1 Referred to as binocular summation, this superiority of binocular viewing exceeds that expected on the basis of two independent chances to detect (probability summation) and is, therefore, generally construed as evidence for binocular “neural” summation. Binocular summation thus provides a useful psychophysical probe for studying the human binocular visual system, including the response properties of the binocular neurons that presumably mediate summation.2,3

There are several reasons to believe that the neural mechanisms underlying binocular summation may be related to those involved in stereoscopic vision. For one, people with defective stereopsis also exhibit reduced binocular summation.4–8 Comparable losses in stereopsis and binocular summation have been described in monkeys9–11 and in cats12,13 raised with induced optical defects that interfere with the development of cortical binocularity. The present experiments explore this possible link between stereopsis and binocular summation further, by measuring binocular summation and the limits for stereopsis using test stimuli placed on disparate portions of the two eyes.

Our interest in this problem is fostered, in part, by the recent work of Schor and colleagues.14–17 Using bar stimuli band-limited in spatial frequency, they found that stereoscopic performance varies with spatial frequency. For example, Schor and Wood14 found that the range of disparities that yields depth sensations is smaller for high spatial frequency bars than it is for lower frequency bars. Schor’s findings bear on recent models of stereopsis18–22 which posit that disparity computations are performed at multiple spatial scales. With Schor’s results in mind, we reasoned that the range of disparities over which binocular neural summation occurs should exhibit a comparable dependence on spatial frequency if, indeed, stereopsis and summation engage common neural mechanisms.

It has already been shown that the amount of binocular summation falls when binocular performance is tested using disparities too large to yield single vision,23–25 indicating that neural summation depends to some degree on retinal disparity. It remained to be determined, however, whether binocular summation occurs over the same disparity ranges as those which
yield stereoscopic depth and single vision. And to the extent that summation is limited in this fashion, does this disparity range depend on the spatial frequency content of the test target? The present experiments sought answers to these two questions.

Materials and Methods

Apparatus

Stimuli were generated electronically on a matched pair of Tektronix (Beaverton, OR) 608 oscilloscopes with P31 phosphor. A mean luminance of 17 cd m⁻² was maintained throughout on each screen, which subtended 8° in width and 6° in height at the viewing distance of 96 cm. The subject viewed these dichoptically through an adjustable mirror stereoscope. On both screens a dark fixation point in the exact center was flanked horizontally by two other points 1.5° to left and right. Nonius points were presented 0.8° above (right eye) and below (left eye) the central spot, and were used to align the stereocope mirrors before each experiment for each subject.

The stimuli extended the entire vertical height of the screen but their horizontal luminance profiles were restricted both spatially and in Fourier composition. The profiles we used were either the third or the tenth derivative of a Gaussian function. These will be referred to as D3 and D10 stimuli respectively. At zero disparity and high contrast the D3 appeared as a blurred bright bar immediately to the left of fixation and a blurred dark bar to the right; the D10 appeared as a blurred bright bar centered on the fixation spot with flanking dark bars on either side (and with fainter bright bars beyond those). The breadth of the Gaussian determined the center spatial frequency of the stimulus, which was set to be 0.75, 2.0 or 6.0 cpd. The bandwidth of these stimuli in Fourier space does not vary with the center spatial frequency, and is 1.42 octave for the D3 and 0.79 octave for the D10. The stimuli were generated by a DEC LSI 11/23 computer (see Halpern et al. for details) which also ran the experiments and analyzed the data.

Procedure

Experiments on summation: The subject initiated each trial by a lever press when the nonius dots were aligned. Two temporal intervals separated by 400 msec were demarcated by audible tones. The stimulus was presented with raised cosine temporal waveform in one of the two intervals, chosen randomly. Pilot experiments revealed no effect on binocular summation at zero disparity of varying the stimulus duration between 20 msec and 1 sec, so the interval duration was set at 60 msec for the remainder of these experiments. The subject pressed another lever to indicate in which interval the stimulus was seen, and auditory feedback of correctness was given.

Contrast thresholds for detecting the stimuli were found by a 2-down-1-up staircase procedure giving 71% correct performance. Three staircases were randomly interleaved. In one, a stimulus was presented to the left eye alone, offset from fixation by a horizontal amount D. This offset was between 5° to the left and 5° to the right of fixation on different staircases but remained constant during any one staircase. On the second interleaved staircase the same stimulus was presented to the right eye alone, but offset to the opposite side of fixation by the same amount D as on the first staircase. On the third interleaved staircase both of these stimuli were presented simultaneously, giving a total disparity of 2D. Thus on each trial the stimulus was equally likely to appear to the left or right of fixation or simultaneously on both sides to give a stereoscopic depth percept if the stimuli were close enough to fixation. This procedure was adopted to minimize the possibility that the direction of gaze might deviate towards one side (which would tend to happen if all trials presented stimuli to the same side), while measuring all three relevant thresholds (left eye, right eye and dichoptic) simultaneously. Each staircase began at roughly 6 dB above threshold; contrast level was altered by 3 dB per step until two turnarounds had been achieved, by 2 dB per step for the next two turnarounds, and by 1 dB thereafter until 15 turnarounds had been completed. The geometric average of the contrast values on the last ten turnarounds was taken as the threshold estimate. Each experiment took about 8 min and was repeated three times to obtain the final threshold estimates. Binocular summation was calculated by dividing the geometric mean of the two monocular thresholds by the corresponding binocular threshold. Note that this cancels any effects due to the edges of the screen, which would affect monocular and binocular stimuli equally.

Experiments on limits for stereopsis and fusion: When the nonius dots were aligned, the subject triggered the trials by pressing a lever. While the lever was held down, the dichoptic stimuli (D3s and D10s) from the summation experiments were presented for 60 msec at 1 sec intervals, at constant suprathreshold contrasts: 0.25 for the 6.0 cpd stimuli and 0.1 for the 2.0 cpd and 0.75 cpd stimuli. The subject adjusted the disparity of the stimuli (which was initially zero) by pressing buttons which signalled the computer to increase or decrease the offset (D) of the stimuli from fixation. This offset was changed in equal but opposite directions for the stimuli presented to the right and left eyes. In the fusion experiments, the subjects
adjusted disparity to the point where fusion gave way to diplopia. In the stereopsis experiments, the subjects adjusted disparity to the upper limit for stereopsis, at which point the apparent depth of the diplopic images collapsed to zero and the two images appeared to lie in the plane of the fixation dots. Each such setting was recorded and the disparity was returned to zero for the beginning of the next trial. In each experiment, the subject completed ten settings in the crossed direction and then ten settings in the uncrossed direction (this order was counterbalanced across subjects and experiments), and the mean of each group of ten settings was taken as the limiting disparity for fusion or stereopsis as appropriate.

Subjects

The subjects were the three authors. All had normal or corrected-to-normal vision and good stereopsis. Informed consent was obtained after the nature of the procedure(s) had been explained fully.

Results

Summation Experiments

In all cases binocular summation was maximal at zero disparity and decreased as the stimulus moved away from the horopter. For example Figure 1A shows the thresholds for the 6.0 cpd D10 stimulus for subject DR plotted as a function of stimulus location. Thresholds were lowest near the fovea and rose progressively towards the retinal periphery as expected. (This subject had slightly lower thresholds overall in the right eye, although this was not true for the lower spatial frequencies as described below.) Note however that within 1° or 2° of fixation the binocular thresholds are clearly much lower than those of either eye stimulated alone. This is illustrated in Figure 1B which shows the ratio between the binocular and the averaged monocular thresholds. The peak value of 1.6 is obtained with zero disparity, and the ratio falls to about 1.1 as disparity increases. Values of the binocular summation ratio above 1.2 are commonly taken as indicating the existence of “neural” summation in excess of probability summation, which predicts ratios near 1.2, depending on the slope of the psychometric function and other factors (see Discussion28,29). Thus in Figure 1B the full range of neural summation extends over some 3° in the disparity domain.

In Figure 2 the dotted line shows the ratios reproduced from Figure 1B. The crosses show the data for this subject with the 2.0 cpd D10 stimulus. Qualitatively the results are similar but now the bandwidth in the disparity domain is larger—between 4° and 6°.

Figure 1. (A) Contrast thresholds for subject DR using the 6.0 cpd D10 stimulus as a function of eccentricity in the left eye (open squares), the right eye (diamonds) and binocularly (filled squares). (B) Ratio of binocular sensitivity to the average monocular sensitivity.

Figure 2. Ratios of binocular to monocular sensitivity for subject DR. Dotted line shows ratios for 6.0 cpd D10 stimulus reproduced from Figure 1B. Crosses show ratios for 2.0 cpd and filled squares for 0.75 cpd. All these were for the D10 stimulus; results with the D3 stimulus at 0.75 cpd are shown as open squares.
depending on the assumed level for probability summation. Finally, the solid squares show the data for 0.75 cpd D10 stimuli. The associated disparity bandwidth must be 4° or less, but a finer estimate is not possible because for disparities near 1° the two dark bars in this stimulus potentially form an ambiguous matching pair. We therefore changed to using D3 stimuli, which do not have this problem, although they have slightly larger bandwidths in their Fourier spectra. The results with a 0.75 cpd D3 are shown as open squares in Figure 2. Again, the disparity bandwidth extends less than 2° on the uncrossed side, but on the crossed side the curve declines more shallowly, and we can only determine the full bandwidth to be in the range 4° to 6°.

For subject RB we used D3 stimuli throughout, and his data for 6.0 and 0.75 cpd are compared in Figure 3. The lower spatial frequency data match those of the previous subject almost exactly. The high spatial frequency bandwidth is also clearly narrower than for the low spatial frequency. However at the high spatial frequency the asymmetry between crossed and uncrossed disparities is complementary for the two subjects: DR had a steeper drop-off from the peak on the uncrossed side, while RB had a very steep drop-off on the crossed side. (For this subject also the monocular thresholds at all eccentricities differed at the high spatial frequency but not at the low, but for RB it was the left eye that was the more sensitive, by a similar amount.)

Finally, subject LH (Fig. 4) conformed to the pattern shown by the other subjects. There is however one anomalous point in the data at 4° uncrossed disparity and 6.0 cpd. This anomaly is caused entirely by a sudden elevation of threshold in the right eye for this stimulus at that eccentricity, and does not reflect on the nature of the binocular summation mechanisms. The data for this subject are more symmetrical around zero disparity than is the case for the other two subjects, and this subject showed higher monocular sensitivity overall in the right eye at both of the spatial frequencies tested.

Limits For Stereopsis and Fusion

The limits of stereopsis and fusion obtained for each subject at each spatial frequency are shown in Table 1 for crossed and uncrossed disparities. Comparison of these data with Figures 1–4 shows that in almost every instance the limit for stereopsis is close to the limit for neural summation, and that both these limits exceed the limits for fusion. To illustrate this point, Figure 5 shows the summation obtained with the 0.75 cpd D3 stimulus, averaged over all three subjects, together with the average fusion and stereopsis limits of the same subjects for the same stimulus at suprathreshold contrast.

Discussion

The results of these experiments clearly show that binocular neural summation occurs only over a limited range of disparity, with performance dropping to the level of probability summation with larger amounts of disparity. Moreover this range varies with spatial frequency, in parallel with the changes that occur in the range for stereopsis. Thus in both cases the correlation with spatial frequency is not linear: in these experiments a reduction of spatial frequency by a factor of 3 (from 6.0 to 2.0 cpd) enlarged the disparity bandwidth of the neural summation by a factor less than 2 for subject DR, and a further reduction in spatial frequency by 2.7 had no further effect. For the
other subjects, eightfold changes in spatial frequency also induced twofold changes in the disparity range. Note that the stimuli we used were limited in their spatial frequency spectrum as well as in space: the D3 stimulus had a full bandwidth of only 1.42 octave at half height, and the D10 stimulus was even more narrowly tuned, 0.79 octave full bandwidth. These values compare favorably with 1.75 octaves for the stimuli used by Schor and colleagues. Together, these data argue against models of depth perception which state that the disparity range correlates directly with spatial frequency.

In order to be more confident about the bandwidth of the neural summation mechanism in the disparity domain, however, it is first necessary to establish accurately the level of performance expected from probability summation alone. The best established model derives from what Green and Swets called the decision threshold model. The level of performance predicted here depends on the slope of the psychometric function, which is best described by a Weibull function with slope parameter $\beta$. For different subjects, $\beta$ is commonly in the range 3–5 (refs. 28, 29 and 31 and unpublished observations on the subjects used in these experiments). The threshold for any stimulus can be estimated on this model by summing the probabilities of detection across the $N$ psychophysical channels which respond (independently) to the stimulus. For our purposes it is noteworthy that the value of $\beta$ has been shown to be constant across spatial frequency.

We can apply this model for probability summation to the case where any $N$ channels (eg, those responding to a stimulus in one eye) are duplicated by an identical set of $N$ independent channels (eg, those responding to the same stimulus presented to the other eye). The increase in sensitivity that is predicted by this model is $^{2^{1/3}}$, which is independent of the number $N$ of monocular channels activated. Thus if $\beta$ is between 3 and 5, values of 1.15 to 1.26 for the binocular summation ratio are within the range expected from probability summation alone.

Our data indeed show that relatively large stimulus disparities yield ratios within this range, and thus confirm that in our experiments we were reaching the disparity region where probability summation alone occurs. In this respect, our results replicate and extend those of Westendorf and Fox who found probability summation alone at a disparity too large to yield fusion. However the stimulus they used was complex in the Fourier domain and contained spatial frequencies higher than those used here, so it is difficult to assess the quantitative sizes of the disparity ranges over which neural summation occurred in these two sets of experiments.

When we come to consider the question of what is the largest disparity at which neural summation can be obtained, we must bear in mind the important distinction between Panum’s fusional area and a larger region over which depth sensations can be evoked despite phenomenal diplopia. Thus previous work indicated that, within 5° of the fovea, fusion could occur only for disparities of less than 0.5°.32,33

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**Table 1. Limiting disparities (deg) for fusion and stereopsis in crossed (C) and uncrossed (U) directions**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Fusion</th>
<th>Stereopsis</th>
<th>Fusion</th>
<th>Stereopsis</th>
<th>Fusion</th>
<th>Stereopsis</th>
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<tbody>
<tr>
<td></td>
<td>C</td>
<td>U</td>
<td>C</td>
<td>U</td>
<td>C</td>
<td>U</td>
</tr>
<tr>
<td>DR</td>
<td>0.20</td>
<td>0.36</td>
<td>1.50</td>
<td>1.20</td>
<td>0.29</td>
<td>0.35</td>
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<tr>
<td>RB</td>
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<td>0.22</td>
<td>1.52</td>
<td>1.74</td>
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<td>0.27</td>
<td>1.31</td>
<td>1.12</td>
<td>0.84</td>
<td>0.66</td>
</tr>
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* D10 for subjects DR and LH; D3 for subject RB.

† D3 for all subjects.

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**Fig. 5. Ratios of binocular to monocular sensitivity for the 0.75 cpd D3 stimulus, averaged across all three subjects. Vertical bars indicate disparity limits for fusion (innermost bars) and for stereopsis (outermost bars) for the same stimulus, averaged across these subjects.**
Depth, however, could be evoked by stimuli with up to 10° disparity, the exact figure depending on the stimulus.14,32,34-37 These results implied that different channels or neural processes might underlie single vision and stereopsis.

The interesting question thus arises as to whether binocular neural summation occurs in the channels which subserves fusion or in those which mediate stereopsis. Our data indicate clearly that neural summation can occur with such stimuli, although over a narrower range of disparities than when the same stimuli are vertically oriented (Fig. 6). Moreover, the vertical range of disparities for summation of long horizontal stimuli matches the range for fusion of long horizontal stimuli (Fig. 6). This result is consistent with the idea that the fusion mechanism, as well as the stereopsis mechanism, sums contrast beyond probabilistic levels.

It may be questioned whether summation to contrast threshold can really occur in the stereoscopic channels in view of the claim that, within the range of disparities that allow stereopsis, depth sensations do not occur unless the stimulus is at least 0.3 log unit above its threshold contrast.40 This figure was derived however by raising contrast until depth appeared, and therefore does not take account of hysteresis in the stereoscopic system. For example, when high contrast gratings of different spatial frequencies are presented to each eye there is an apparent tilt in depth of the fused percept, and this tilt persists even when the contrast of one of the gratings is lowered virtually down to its detection threshold.44 When the contrast of that grating is raised from threshold there is a delay in the reestablishment of depth perception, which may be due to the presence of strong inhibitory interactions between channels in the stereoscopic system.45 It has also been shown that depth channels can be activated by dynamic random-dot stereograms at or below the monocular detection threshold.46 Most recently, it has been found that although stereoacuity deteriorates at low contrasts, near the detection threshold, it is not lost altogether.43 Summation to contrast threshold within the stereoscopic channels therefore cannot be ruled out on the evidence we have at present.

![Graph showing ratios of binocular to monocular sensitivity](image-url)
It may also be questioned why summation declines with increasing disparity, whereas apparent depth increases and then decreases as disparity is increased over the same range of values. It might be suggested that the fusion mechanism is entirely responsible for the summation that we observed at zero disparity. However, if that were the case then summation should first decline as disparity increases to the fusion limit, but then summation should rise again as disparity increases further, from the fusion limit to the point where the apparent depth is maximal, because this point lies well beyond the range of fusion. Our data do not show such a rise (Figs. 1–6). Clearly, the apparent depth of a stimulus is not given just by the strength of the signal that arises from summing the inputs to the stereopsis mechanism. Instead, we prefer to think that the apparent distance of a stimulus is computed by comparing information across channels which had previously integrated information from the two eyes. Such computation might involve, for example, taking the ratio of the signals in the crossed and uncrossed channels, or finding the peak activity among channels tuned to different locations along the depth domain. Thus at any given disparity the amount of summation depends on the properties of the neural mechanisms which exist within the channels which are dedicated to that disparity, while apparent depth is encoded across the outputs of the different disparity channels.

A further point concerns the existence of asymmetries between crossed and uncrossed disparities. Lasley et al., using narrow line stimuli of broad Fourier composition, discovered that crossed disparities were identified more accurately in 74% of a group of 64 subjects. However, Herring and Bechtold found no such effect across 20 subjects, using somewhat broader bar stimuli. Schor and Badcock also observed no crossed-uncrossed difference in stereo discrimination thresholds in their three subjects at any spatial frequency. In contrast, Schor and Wood found that suprathreshold stereoscopic responses occurred over a wider range of uncrossed disparities for their two normal subjects at low spatial frequencies. Also, Schor and Howarth reported that low spatial frequency targets appear to be at uncrossed disparities even when they are actually in the plane of fixation. Our data (Figs. 1–4) show not only that individual differences can occur in the relative responsiveness to crossed and uncrossed disparities, as Richards first demonstrated, but also that these differences may be selective for spatial frequency. These results suggest that the crossed and uncrossed pools are both collections of channels tuned to a number of different spatial frequencies.

Finally, to illustrate the ecological validity of the phenomenon we have studied, it is instructive to consider the following situation. Imagine an observer with 65 mm interpupillary distance who is fixating a point 62 cm distant. Objects at optical infinity then yield 3.0° uncrossed disparity and objects 31 cm from the observer produce 3.0° crossed disparity. Thus under these conditions the region within which stereoscopic depth awareness and binocular neural summation can occur fills almost the entire three-dimensional extent of the binocular visual field. This simple calculation emphasizes the importance of considering the range of disparities which can be encountered both during development and during adult life.

**Key words:** stereopsis, binocular summation, disparity, fusion, contrast threshold

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