Binocular enhancement of visual acuity

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Using a computerized test system, we compared binocular and monocular visual optotype acuity, varying both contrast and contrast disparity between the two eyes. When contrast was the same in the two eyes, binocular acuity was better than best monocular acuity by an average of 0.045 log minimum angle of resolution, or 11%. When contrast differed in the two eyes, binocular acuity in most but not all cases was still better than the monocular acuity of the eye that received the higher contrast. This binocular advantage became smaller but remained significant as contrast disparity became larger. These results are most simply explained by threshold contrast summation of high-spatial-frequency letter components.

INTRODUCTION

Under a wide range of conditions, vision with two eyes is better than vision with one. With detection and discrimination tasks, binocular superiority is often attributed to two components: a probabilistic effect based on the idea that the two eyes each have independent opportunities for detection, and a neural component based on synaptic convergence of monocular inputs. Together these enhancements constitute what is often called binocular summation. Contrast sensitivity is enhanced by 40–50% with binocular viewing[1–6]; brightness perception,[7–10] contrast masking and discrimination,[11,12] and reaction time to the onset of grating stimuli[13,14] exhibit binocular improvement (with somewhat less agreement) of the order of 30–70%. Numerous studies in the past several decades have been devoted to understanding binocular enhancement and the conditions under which it occurs (see Refs. 15–17 for reviews).

In this paper we examine a type of binocular interaction that has received little attention in the binocular-summation literature—visual acuity measured with optotypes. Optotype acuity is of interest for several theoretical and practical reasons. First, the stimuli used in the task and the task itself are more complex than are those used in traditional binocular-summation experiments on detection and simple discrimination. Previous studies have found the magnitude of binocular summation to be inversely related to both types of complexity,[15,18] suggesting that there may be more than one mechanism underlying binocular summation for simple and complex tasks. For the experiments reported in this paper we used a complex acuity task, but we found that the summation effects observed are explicable by the same mechanisms previously found to underlie summation with simple detection, without recourse to task complexity.

Second, letter stimuli contain energy at many orientations and spatial frequencies, unlike grating and other band-limited stimuli that typically are used to measure contrast detection and discrimination thresholds. At acuity threshold, where letters are small, most of the information that distinguishes the optotype forms is contained in high retinal spatial frequencies of the letter images.[19] Although threshold studies that use gratings normally show binocular-enhancement effects that are constant over spatial frequency,[1,3,20] they generally make measurements only in the low-frequency and midfrequency ranges, invariably below the high spatial frequencies that are needed to resolve small features such as the gap in a Landolt C. Indeed, spatial resolution, an important determinant of acuity, can be viewed usefully as a spatial-frequency limit beyond which effective visual processing breaks down. Thus, if summation effects in an acuity task differ from those in a typical lower-frequency task, it is at least possible that the frequency content of the stimulus has a role in the difference.

Finally, binocular-acuity interactions may bear on rehabilitation strategies applied to individuals with ocular pathology in that they may provide an estimate of the functional penalty that might result from not utilizing binocular vision for tasks associated with visual acuity, such as reading, or in not prescribing binocular aids for such tasks.[21]

Surprisingly few studies of acuity enhancement have been performed. Those that exist[22–24] have found binocular superiority in acuity tasks by using grating stimuli, Landolt rings, and Snellen letters. However, Horowitz[23] argued that much of the binocular summation found in earlier studies was simply a result of artifactual reductions of monocular acuity that were caused by failure to control for pupil size and by differences in intensity and pattern in the two eyes. He found that a smaller amount of summation remained after the removal of those artifacts.

Home[25] found a 40% improvement of binocular over monocular Landolt C acuity at a low contrast of 1%, but at contrasts higher than 30% improvement fell to ~9%. The

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binocular advantage in contrast detection tasks that use circular patches and large letter stimuli was 40–50%, similar to that found for low-contrast acuity.

More recently, Frisen and Lindblom[18] studied binocular summation by using a variety of visual tasks, including acuity measured with Landolt rings and broken lines. They found that binocular acuity exceeded monocular acuity by ~9% in both acuity tests, a result similar to those of the earlier studies.[22,23,25] Their main finding, however, was that summation levels were highest (56%) for a simple detection task as compared with 0% for a complex pattern-recognition task.

In a study more closely related to ours, Pardhan and Elliott[26] used the Early Treatment Diabetic Retinopathy Study (ETDRS) chart,[27] now marketed as the Lighthouse Distance Visual Acuity Test, to compare monocular and binocular acuity in subjects who had two healthy eyes, monocular cataracts, or binocular cataracts of unequal densities. They observed binocular enhancement of approximately one half a line of the letter chart for normal subjects but little or no enhancement for the cataractous subjects. Since monocular cataracts and binocular cataracts of different densities produce unequal retinal illuminances and contrasts in the two eyes, it is difficult to determine whether the lack of acuity enhancement observed by Pardhan and Elliott in subjects with cataracts is due to interocular contrast or to retinal-illuminance differences. Also, because there are only three versions of the ETDRS printed letter chart, the number of observations made by individual subjects was restricted by chart familiarity, and manipulation of stimulus characteristics such as contrast in the two eyes was not possible.

The present study used normally sighted observers to compare monocular and binocular visual acuity. Our objective was to determine (1) the extent of enhancement, if any, of binocular acuity relative to monocular acuity as a function of letter contrast and (2) the effect on acuity of interocular differences in contrast. Our computerized acuity-test system overcomes the limitations of printed letter charts by permitting control of contrast and by randomizing letter combinations to permit within-subject repeated testing and thus higher test reliability.[28,29]

METHODS

Sloan characters were displayed on a Mitsubishi color monitor driven by an X-Windows (X11) server residing on a Silicon Graphics IRIS 4D/25 graphic workstation with a StereoGraphics Corporation stereo-display system. The final resolution of the display was 1280 horizontal × 512 vertical pixels, and the luminance was 88.3 cd/m^2. The stereo-display system, which is responsible for the low vertical resolution, permitted us to present different stimuli to each eye simultaneously through a pair of liquid-crystal shutter glasses synchronized to the monitor frame rate of 120 Hz. The glasses provided an apparently flicker-free 60-Hz image to each eye, with 32% transmittance and negligible cross talk (~1.1% transmittance through the closed shutter). Client software, which actually ran the experiments via a local network, resided on a Sun SparcStation 1.

D O V H R

Fig. 1. Line of five Sloan characters, similar to those found on the Lighthouse–ETDRS chart and those used in the experiments.

We intended to mimic as closely as possible the Lighthouse–ETDRS chart, which incorporates accepted principles established by Bailey and Lovie[30] and by Ferris *et al.*[27] Letters were displayed in lines of five characters, separated from one another and from the edge of the screen by the width of one character, as shown in Fig. 1.

One line was displayed and tested at a time. To eliminate the possibility that subjects could memorize letter sequences because of repeated testing, we used computer-generated random combinations of five of the ten Sloan letters for each line. Letters were not repeated within a line and were displayed with approximately equal frequency in the course of each complete acuity measurement.

Letters were generated by use of the font-design language METAFONT, which translates geometric definitions of type into pixel representation. The advantage of using METAFONT is that a single program can be used to generate optotypes of any size. Sloan characters are designed in a 5 × 5 grid such that the stroke width of a character is one fifth of the overall width.

Our optotypes were intended to vary in size by 0.05 log unit between lines, as compared with the 0.1-log-unit step size that is used in the charts that were emulated, to improve the precision of acuity measurements. Digitization error caused sizes to depart slightly from their intended values, of course, but for all letters the size along the (vertical) dimension of lowest resolution differed from its intended value by no more than 3% and by only 1.5% on average. The letter sizes that we used ranged from 2.2 to 0.43 cm.

To reduce the size of the letters at the eye, subjects viewed the display at a distance of 95 cm through the objective lenses of a reversed pair of Minolta 10 × 25 wide-angle pocket binoculars that had a transmittance of 65% as measured on an optical bench. At the resulting optical distance of 950 cm, the range of character sizes that we employed permitted us to test acuities in the range of 0.2 to −0.5 log minimum angle of resolution (MAR) (20/32 to 20/6.3 Snellen equivalent).

Subjects were constrained by a chin rest and viewed the display through the binoculars and shutter glasses, both of which were mounted on an optical bench directly in front of the subject. The binoculars have adjustable interocular distance, and the image was carefully centered for each eye through the sighting tubes at the start of each session. The luminance of the screen, after attenuation by both the shutter glasses and binoculars, was ~18 cd/m^2 and provided the only source of light in the otherwise darkened room.

We tested four highly practiced observers, aged 29–40 years, including the authors. Two of these observers were emmetropic, and two were slightly myopic. The myopic subjects wore their spectacles for correction. All the subjects were aware of the identity and number of characters in the Sloan set (C, D, H, K, N, O, R, S, V, and Z).

A one-up-one-down staircase procedure was used in which character size was decreased when the subject read three or more characters in a line correctly or was increased when three or more characters in a line were read incorrectly. These staircases estimate the 50% correct identification level on the psychometric function. A step size of 0.1 log unit (25.8% size difference between lines) was used before the first reversal; afterward it was reduced to 0.05 log unit (12.2%) for the remainder of the staircase. Subjects were given as much time as they needed to read each line aloud and were told ahead of time to guess when they were unsure, so that five responses were obtained for each line. The experimenter typed the responses into the computer, and the procedure was run until there were 12 reversals of the staircase. The time taken by observers to read a line ranged from ~5 s when the letters were clearly visible to at most 30 s for lines close to the acuity limit.

A modification of the method recommended by Ferris *et al.*,[27] in which credit is awarded for each letter read correctly by the subject, was used to measure acuity. In our staircase method the final acuity score of an individual after completing one run is the average of 12 reversals. The score of each reversal is adjusted to reflect the number of incorrect responses on the line. For example, when a subject reads down to the −0.1 log MAR line and then reads only one of five letters correctly in that line, character size is increased. The score for this reversal is −0.06 log MAR because each of the four characters read incorrectly adds 0.01 to the acuity score. He or she then reads three of five correctly on the −0.05 log MAR line, so character size is decreased, the score for this reversal is −0.03 log MAR, and so on.

We used four contrast levels in the experiments: 0.313, 0.465, 0.679, and 0.994. Contrast between the foreground (character) luminance L_{fg} and the background luminance L_{bg} was defined as $L_{bg} - L_{fg}/L_{bg}$. We varied contrast by changing only the foreground luminance.

Subjects viewed all the displays through both the binoculars and the shutter glasses. There were three viewing conditions. For the monocular condition background luminance was presented to one eye while the other eye received letters at each of the four contrasts. For the binocular condition both eyes received letters of equal contrast for all four contrasts.

For the third viewing condition interocular contrast differences were introduced in one of two ways. In one method, one eye was presented with a fixed high-contrast target (0.994) while the other eye viewed the three lower-contrast targets. In the other method, one eye viewed a fixed low-contrast (0.313) target while the other eye viewed the three higher-contrast targets. Both the left and the right eyes were tested with the fixed low and fixed high contrast. Near acuity threshold, mean luminance was approximately equal in the two eyes, since the background (which was the same in both eyes) covered a much larger area of the display than did the foreground and was therefore the main component of the mean luminance.

RESULTS

Figure 2 plots log MAR acuity as a function of contrast for the binocular and monocular conditions for four subjects. All the subjects showed binocular enhancement (i.e., binocular acuity was better than best monocular acuity) at the three highest contrasts; two of the four subjects had better monocular acuity at the lowest contrast. For each subject acuity improved with each increment in contrast.

The enhancement effect is summarized in Fig. 3, which shows log MAR binocular improvement relative to best monocular performance. Mean summation for all the subjects except RBC at the three highest contrasts was 0.034 log MAR; for RBC it was 0.086 log MAR. The summation level seems to be independent of contrast over the 0.465–0.994 range. The average summation level of the three similar subjects represents a third of a line of a standard letter chart, such as the Lighthouse–ETDRS or the Bailey–Lovie chart, or nearly two letters. Subject RBC's average enhancement was 4.33 letters, close to an entire line.

The results obtained when different contrasts were presented to the two eyes are shown in Fig. 4. Figure 4(a) shows average data resulting from a fixed low contrast (0.313) in one eye, and a varying contrast in the other. Acuity improved steadily as the contrast in the varying (and higher-contrast) eye was increased. Figure 4(b) shows average data resulting from a fixed high contrast (0.994) in one eye and a varying contrast in the other. These data show relatively constant acuity regardless of the contrast in the varying (and lower-contrast) eye. Taken as a whole, the results shown in Fig. 4 suggest that when the two eyes viewed unequal contrasts performance was governed by the eye that received the higher contrast.

Although the general trend of the data in Fig. 4 suggests that under these conditions the eye that received the lower contrast contributed little to binocular acuity, in fact binocular acuities thus obtained were typically better than those of the higher-contrast eye when tested monocularly. Figure 5 shows average binocular enhancement (in log MAR) relative to the monocular acuity of the higher-contrast eye.

Figure 5(a) shows the average binocular enhancement obtained in the presence of a fixed low contrast (0.313) in one eye, as a function of the varying (same or higher) contrast in the other eye, for the three subjects who exhibited enhancement in this condition (all subjects except AA). Enhancement was generally greatest (~0.06 log MAR) when the contrast in the fixed eye matched that in the varying eye (indicated by the arrow). Observer AA's binocular acuity was worse than his monocular acuity, in this unequal contrast condition, by an average of 0.03 log MAR.

Figure 5(b) plots average enhancement levels in the case of a fixed high contrast (0.994), as a function of the varying (same or lower) contrast in the other eye, for three subjects except EBJ. As in Fig. 5(a), this graph shows generally higher levels of enhancement when contrasts were either the same (indicated by the arrow) or closely matched. Observer EBJ's binocular acuity was worse than that of the higher-contrast eye by 0.02 log MAR on average.

DISCUSSION

Binocular acuities of four subjects were better than their best monocular acuities by an average of 0.045 log MAR, largely independent of contrast (Figs. 2 and 3). This corresponds to an 11% difference in size between letters that can be read binocularly and those that can be read

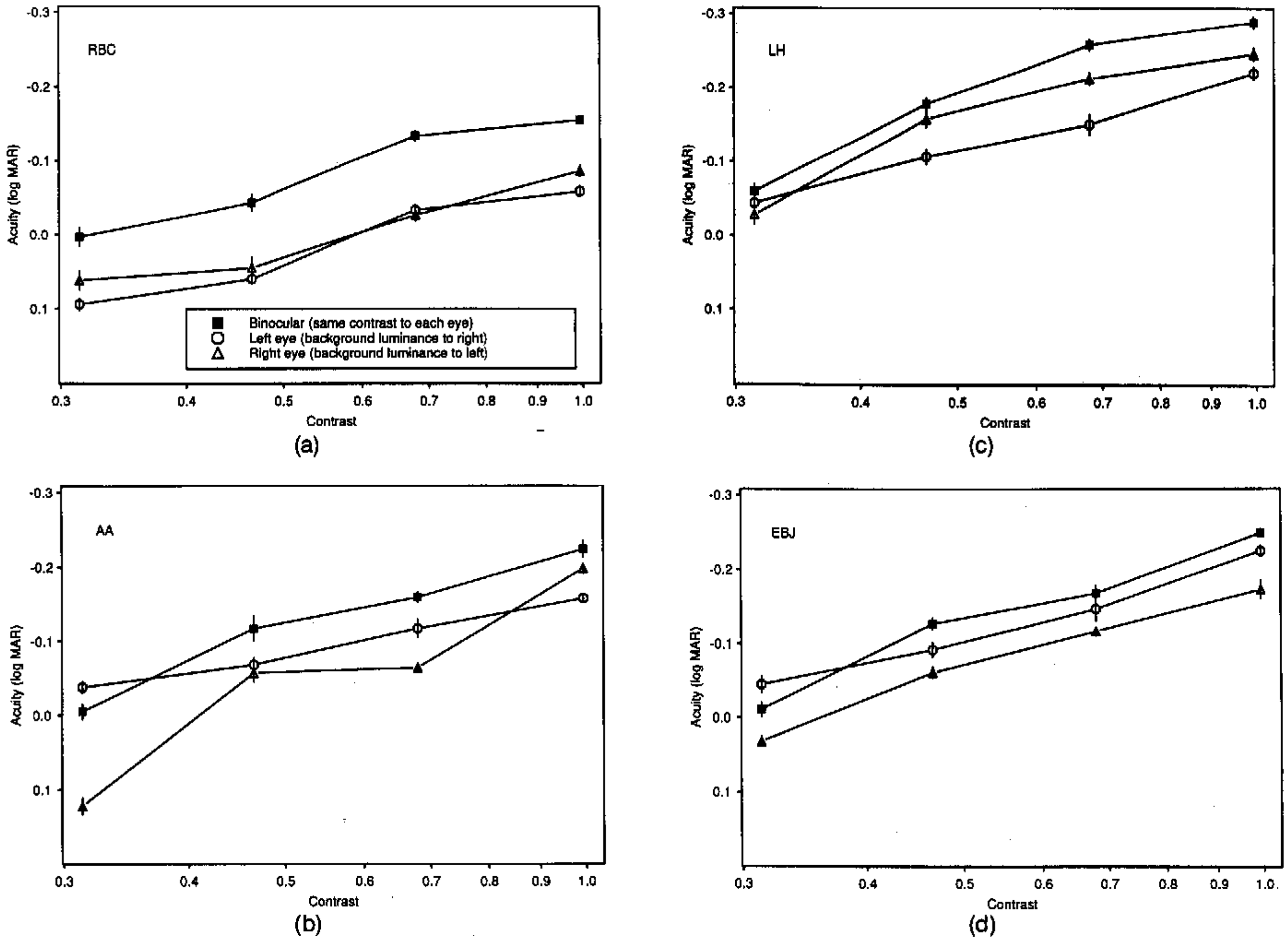

Fig. 2. Monocular and binocular acuities as a function of contrast for four subjects. Error bars indicate ±1 standard error of the mean.

monocularly and agrees well with previous reports of acuity summation in slightly different tasks.[18,22,23,25,26] When contrasts were unequal in the two eyes, acuities varied in accordance with the eye that received the higher contrast (Fig. 4). Compared with the monocular acuities of the eyes that received the higher contrast, however, binocular performance was still better in most cases, but the magnitude of the improvement typically decreased with contrast disparity, ranging from 0.06 to 0.03 log MAR on average (Fig. 5). For two subjects summation was observed in just one of the contrast-disparity conditions, whereas in the other condition binocular performance was actually worse than monocular performance. Possible reasons for this variability include differing effects of binocular rivalry or ocular dominance, although no firm conclusion can be reached on the basis of the available data.

How can we explain these results? Much of the early interest in suprathreshold binocular interactions focused on binocular versus monocular brightness perception. In general, perceived binocular brightness was found under most conditions to be well described by the average of monocular brightnesses, so binocular enhancement was not observed relative to best monocular performance (see Refs. 7 and 17 for reviews). More-recent suprathreshold studies of contrast interactions have found it difficult to apply any single model to apparent binocular contrast.[12,31,32] Contrast discrimination shows some binocular enhancement, but only at pedestal contrasts much lower than those that we used in the present experiments.[5]

Probability summation of letter identification, in which each eye's independent chance of identifying the letters would result in better binocular than monocular performance, may have contributed to the observed enhancement. However, probability summation would be significant only in cases in which sensitivities in the two eyes are closely matched; thus the results from the contrast-disparity condition argue against this possibility. The influence of a probabilistic advantage would diminish rapidly as soon as one eye received a lower contrast, since that eye would not be contributing equally to the response. Instead we found that, for those subjects who exhibit enhancement, enhancement levels depend to a small degree on contrast disparity but remain significant even for the largest interocular difference in contrast. Thus probability summation of letter identification is likely to be, at best, only a weak contributor to our results.

A better explanation of our results is that the summation that was observed in the letter-identification domain was caused by the summation's occurring in the contrast domain. In other words, although visual acuity is a suprathreshold contrast task, our observed binocular enhancement can be explained most simply by threshold

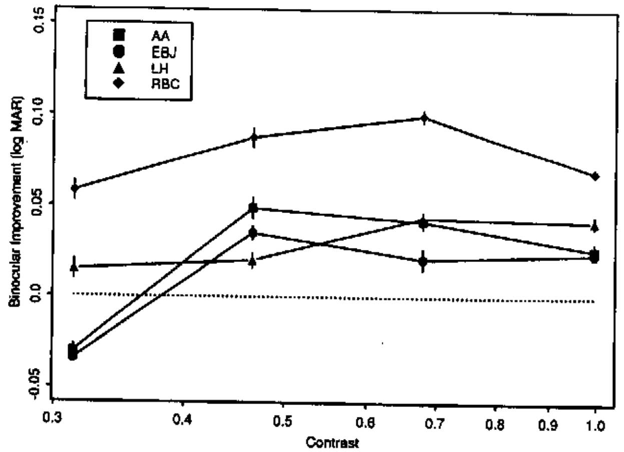

Fig. 3. Binocular enhancement (binocular minus best monocular performance) as a function of contrast for four subjects. The dotted line indicates no enhancement. Error bars are ±1 standard error of the mean.

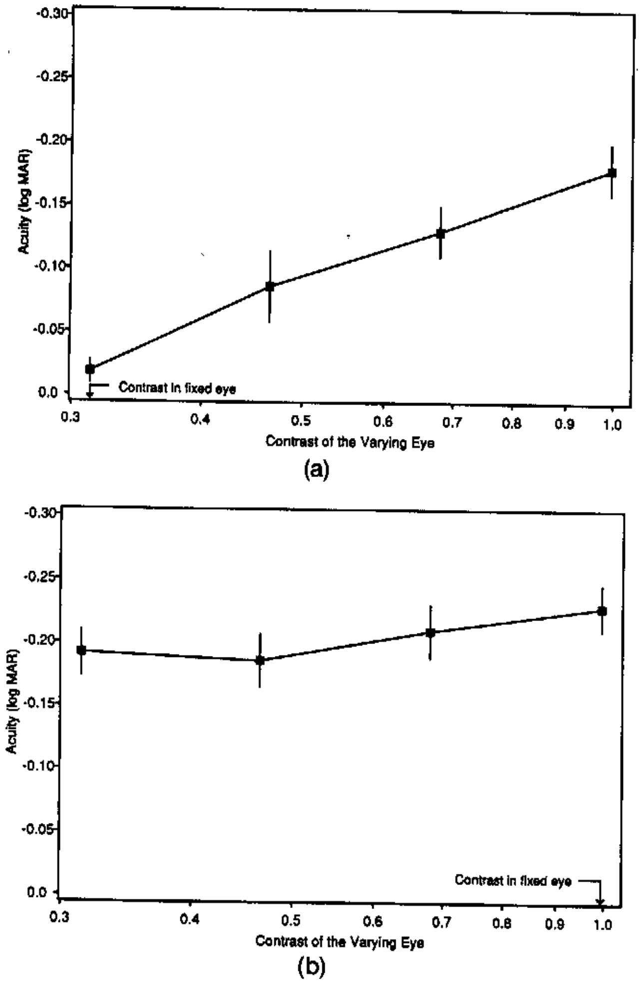

Fig. 4. Average binocular acuity (log MAR) for the condition in which one eye was presented with a fixed contrast (low or high) and contrast to the other eye was varied. Contrast of the varying eye is plotted on the x axis. (a) The fixed eye receives a contrast of 0.313 (indicated by the arrow); the other eye is presented with each of the other contrasts. (b) The fixed eye receives a contrast of 0.994 (indicated by the arrow); the other eye views each of the other contrasts. In both (a) and (b) the data are averaged across eyes and across all subjects. Error bars indicate ±1 standard error of the mean.

summation of high spatial frequencies. There is no need to derive a separate suprathreshold model or mechanism to describe the bulk of our data or to invoke task complexity.

Figure 6 schematizes this concept, showing binocular and monocular contrast-sensitivity functions shifted vertically with respect to one another to indicate binocular enhancement. The shift along the spatial-frequency axis that results from the contrast enhancement represents the expected acuity enhancement.

We assume that, at acuity threshold, the spatial frequencies of the components which we presume to be critical in the discrimination are sufficiently high to fall near their own contrast threshold. Our observed acuity enhancement may then be accounted for by threshold contrast summation of these high-spatial-frequency components, which effectively increases the high-spatial-frequency cutoff of the contrast-sensitivity function. Acuity (in MAR)

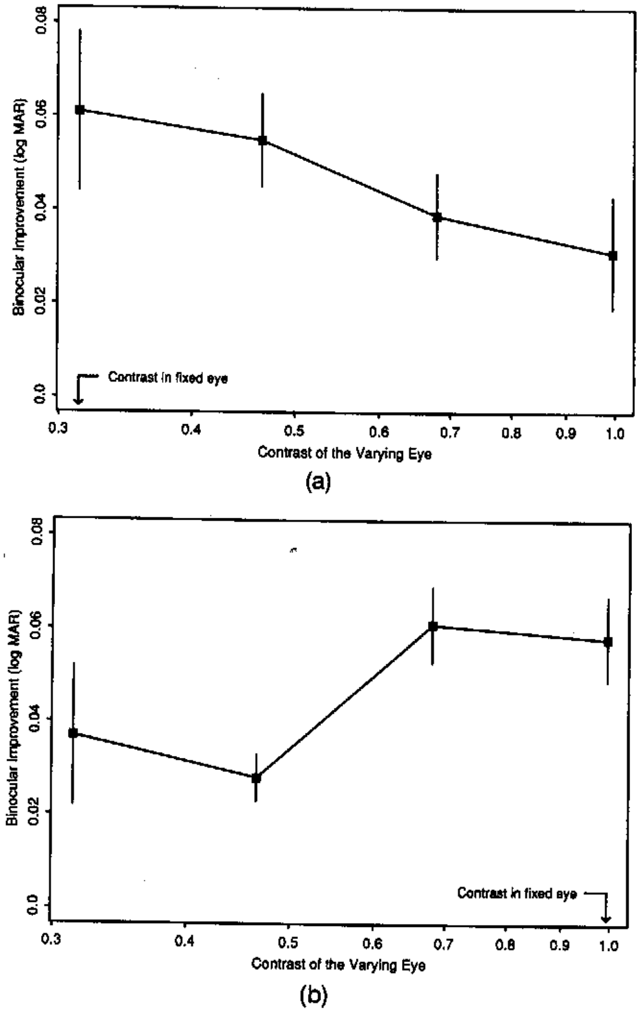

Fig. 5. Average binocular enhancement (log MAR) relative to the monocular acuity of the higher-contrast eye for the unequal contrast conditions. These data are the binocular acuities for each contrast-disparity condition (averaged in Fig. 4) minus the corresponding monocular acuities of the higher-contrast eye (shown in Fig. 2). (a) Average data of three subjects (except for AA) for the condition in which the fixed eye receives a contrast of 0.313 (indicated by the arrow). (b) Average data of three subjects (except for EBJ) for the condition in which the fixed eye receives a contrast of 0.994 (indicated by the arrow). In both (a) and (b) the data are averaged across eyes. Error bars indicate ±1 standard error of the mean.

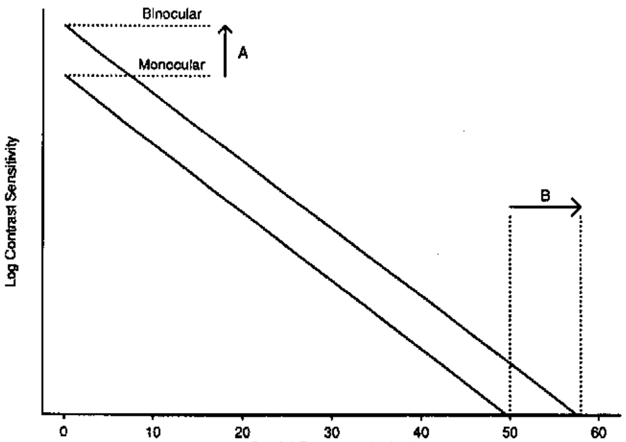

Fig. 6. How binocular summation at contrast threshold can increase spatial-frequency resolution. A, Contrast summation. B, The resultant shift in the high-spatial-frequency cutoff, provided that certain assumptions hold (see text).

can be converted into cycles per degree (c/deg) by use of the equation c/deg = 30/MAR,[33] which assumes that one fifth of the retinal size of a letter corresponds to one-half cycle of the highest-spatial-frequency component that must be resolved for successful letter identification.[19,34] By use of this relation most acuities that we measured correspond to very high resolutions, in the range of 30–57 c/deg.

This explanation of threshold contrast summation, of course, also requires that resolution be the limiting factor in our measurement. This notion has received strong support from the recent research results of Parish and Sperling,[35] who showed that identification of spatially bandpass-filtered images of letters in bandpass-filtered noise is independent of retinal-image size over a 32:1 range of letter sizes.

Quantitatively, the improvement in binocular acuity expected from the ubiquitous $\sqrt{2}$ summation in binocular contrast detection[1,5,36,37] is ~4 c/deg. This represents an improvement in acuity of 0.035 log MAR at a spatial frequency that corresponds to averaged acuities at the two highest contrasts, if we assume, as above, that acuity of 0 log MAR corresponds to a resolution of 30 c/deg,[19,33,34] that letter acuity improves in proportion to spatial-frequency resolution, and that the slope of the high-spatial-frequency end of the contrast-sensitivity function is similar to that in Campbell and Green.[1] The prediction agrees well with three subjects' results, in which average enhancement of binocular over best monocular acuity was 0.034 log MAR for the three highest contrasts.

The fourth subject (RBC) had an even larger enhancement effect, which could be due to his lower average acuity, to a more gradual falloff of contrast sensitivity with spatial frequency, or both. Note that our explanation predicts enhancement at all high-spatial-frequency cutoffs, with lower acuity producing a larger percentage of binocular improvement. That is, at lower acuities, at which the monocular and binocular high-spatial-frequency cutoffs are at lower spatial frequencies, an improvement of 4 c/deg represents a larger improvement in log MAR than at higher acuities. Under the threshold contrast summation hypothesis, one would expect RBC to exhibit, on the basis of his lower baseline acuity, ~0.02 log MAR more enhancement than did the other observers. His lower acuity alone, then, correctly predicts ~40% of his higher enhancement effect.

The enhancement found when the two eyes were presented with different contrasts is also predicted by models of threshold contrast summation.[36,37] Whereas these and other comparable models may differ in their ability to account for all observed binocular interactions,[37] all are in some degree sensitive to differences in the monocular sensitivities that contribute to the binocular response. That is, summation magnitude is predicted to be a function of contrast similarity between the eyes such that levels of enhancement are largest when contrasts (or sensitivities) are equal and fall off when contrasts are maximally different. Our results exhibited this pattern to a large extent, although two subjects showed a worsening of binocular acuity relative to monocular acuity in one of the contrast-disparity conditions, which would not be predicted by these models or by simple probability summation. Similar inhibition of binocular performance has been found for contrast detection with unequal illuminance in the two eyes[6,20] but not for visual acuity of subjects with cataracts.[26]

A somewhat different explanation of binocular-acuity enhancement, based on artifactual changes in pupil size, has been offered to account for earlier acuity-enhancement results.[23] Pupil size affects both retinal illuminance and image quality, but in ways that would have opposite effects on visual resolving capacity. Increasing pupil diameter increases retinal illuminance, which enhances sensitivity, but it also permits light to pass through larger areas of the eye's refractive surfaces, further exposing it to the negative effects of the Seidel aberrations.

Horowitz[23] argued that, when monocular testing is performed with occlusion of the untested eye, the resultant larger pupil size in the tested eye worsens acuity. He found that, on average, monocular acuity was better with smaller pupils; therefore, over the range of luminances and pupil sizes that he used, minimizing aberrations seems to affect acuity more positively than does maximizing retinal illuminance.

Similarly, Campbell and Green[38] found that smaller pupils yielded better high-spatial-frequency sensitivity when retinal illuminance was kept constant. However, Sloane *et al.*[39] and Kay and Morrison,[40] who permitted retinal illuminance to vary naturally with pupil size, found pupil size to have little effect on spatial contrast sensitivity at any luminance level.

In any case, pupil size is not likely to have been a factor in our study since, at the acuity limit in all viewing conditions, the mean luminance presented to each eye was closely matched, thus keeping artifactual differences in pupil size between conditions and eyes to a minimum. Specifically, when the letters that make up the foreground of the display were small relative to the background, as occurs near the acuity limit, the overall luminance of the display differed by no more than 2.5–7% in the two eyes in the worst case, depending on the observer's acuity.

Frisen and Lindblom[18] proposed a hierarchical model to explain their result that more-complex visual tasks yield less binocular summation. In their model, the magnitude of summation depends on the relative contribution to the response of monocularly and binocularly driven cells in the visual cortical layers. They proposed that lower-level monocular cells are the primary processors of simple visual stimuli and that significant summation arises because of their independence. Complex stimuli/visual tasks (the two terms are used interchangeably in the explanation of their model), on the other hand, are likely to be processed by higher-level binocular units, which according to the Frisen–Lindblom hypothesis yield less summation.

It is unclear to what degree the output of the lower-level units would contribute to the later stages of processing during a complex task with complex stimuli, however. If our explanation of our results is correct, then summation arises from a process considered by the Frisen–Lindblom model to be low-level contrast detection, even though our task and stimuli are complex. In the Frisen–Lindblom framework our contrast-disparity results could be taken as evidence for summation in binocular units, since monocular units would not be contributing equally to the response, and therefore summation of a probabilistic nature would presumably not arise from them.

Our explanation draws attention to the appropriate dimension along which summation occurs. It is somewhat misleading to compare, in percentage terms, the amount of summation that occurs in different task domains (e.g., contrast detection and letter acuity) because the implication is that smaller percentages indicate less summation. The percentage improvement that we and others find for acuity, although it is numerically smaller than the 40–50% summation found in contrast detection, is what would be expected from typical summation in the contrast domain (40–50%) that occurs at our base acuity. It is presumed that contrast summation makes the stimulus more salient for subsequent processing, in this case, letter identification. Hence it is possible that the summation observed in many complex tasks arises from a similar amount of contrast summation, but the amount observed in percentage terms depends on the dimension along which it is being measured.

Results of the Home study[25] also support this notion. In the two tasks measuring contrast-detection thresholds (one by use of circular patches and the other by use of large letters) binocular improvement was 40–50%, as found by many others in research that used similar tasks. In his acuity task utilizing Landolt C's, Home found binocular improvement of 9% for contrasts above 30%, similar to our result. However, when contrast was lowered to 1% in the same task, summation increased to 40%, close to what was found for contrast-detection tasks. Home explains that this result can be attributed to the fact that, at the lowest contrast, the acuity task effectively becomes one of contrast detection for a large stimulus. In fact, the steady increase of percentage binocular summation with decreasing contrast (from 30% to as low as 1%) in the acuity task would be expected if a single contrast-summation factor was responsible (see Fig. 6). As low contrasts are decreased further, acuities become worse, so an improvement that is due to summation in the contrast domain becomes a larger percentage of the baseline acuity.

In an interesting physiological correlate to our enhancement data that bears on the earlier discussion of the Frisen–Lindblom model, Freeman and Ohzawa[41] measured the binocular interaction of simple cells in cat visual cortex as a function of contrast mismatch in the two eyes. Binocular interaction was estimated from phase-tuning curves, which typically show higher rates of cell discharge when in-phase gratings are presented to the two eyes. They expected that stimulating one eye with a lower contrast would cause that eye to lose its influence on the discharge of the cell under study, resulting in a reduction of phase-specific binocular interaction. However, they found that, even for conditions in which contrasts differed by as much as a log unit, the shape of the tuning curve remained largely the same. Thus it appears that the eye receiving the lower contrast was still contributing to the binocular response and that summation from these binocular units was possible even in these conditions. The maximum discharge rate of the cell, however, was reduced compared with the condition of equal contrasts.

Our psychophysical findings are consistent with these physiological data. In conditions of contrast mismatch, our results showed that the form of the binocular interaction (enhancement) remained largely the same when compared with conditions of equal contrast. Like the cell discharge rate, however, the magnitude of the observed enhancement became less (but remained significant) as contrast difference increased.

CONCLUSION

We observed an average binocular enhancement of visual acuity of 11% in both the equal and unequal contrast conditions. This significant improvement can be accounted for largely by threshold contrast summation, which is perhaps counterintuitive, given the fact that high contrast is used in the measurement of acuity. Indeed, the similarity of this task to day-to-day visual activities that involve high-contrast small letters, such as reading, makes it likely that such activities will also benefit from binocular enhancement.

The enhancement observed in our unmatched-contrast condition indicates that it is worthwhile for clinicians to consider the benefit of using two eyes in individuals who have inoperable monocular or binocular cataracts, and other contrast-reducing conditions, instead of maximizing function in the better eye. Maximizing function in a single eye might not be the best strategy for high-resolution tasks, since there may be a worsening of performance in the absence of both eyes' input.

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