Enhancement of Resolution Acuity in a Half-Binocular Viewing Condition

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Purpose. To investigate the effect of interocular stimulus similarity on foveal resolution acuity.

Methods. Liquid crystal shutter goggles synchronized with the monitor refresh rate were used to present a Landolt C and surround bars to one or both eyes, in four viewing conditions (monocular, dichoptic, half-binocular, and binocular). Resolution acuity was measured in each condition in 22 normally sighted adults.

Results. Resolution acuity was significantly better in the binocular condition than in the other three viewing conditions (binocular summation) and was significantly better in the half-binocular condition (with target presented to the test eye and bars presented to both eyes) than in the dichoptic condition (target presented to the test eye and bars presented to the nontested eye only).

Conclusions. Monocular resolution acuity depends in part on interocular similarities of the stimulus surrounding the central target. This finding may have implications in the design of stimuli for vision-training therapies. (*Invest Ophthalmol Vis Sci.* 2010;51:6066–6069) DOI:10.1167/iovs.09-4896

Visual performance is better when identical images are presented to both eyes than when an image is presented to one eye only.[1–4] This facilitatory phenomenon is called binocular summation and has been reported for detection, recognition, discrimination, and reaction time measures of visual acuity, and for contrast sensitivity.[1,5] When dissimilar images are obtained in corresponding retinal areas, the right and left percepts are said to be rivalrous, which may result in an alternation between the percepts[1] and a reduction in visual performance. In this case, neither fusion nor summation is experienced. If different areas in the two retinas are stimulated simultaneously a single mixed impression results without (spatial) conflict, and the two different stimuli can be integrated into a single image.

In addition to interocular effects, visual performance is affected by the spatial proximity of visual stimuli, and the effect may be facilitatory or inhibitory. The term *crowding* was used by Ehlers[6] to describe the inhibitory effect of distractors adjacent to a test letter. More recently, a range of terms have been used to describe this type of effect, including lateral masking, lateral inhibition, and contour interaction. Crowding and contour interaction are thought to be cortical phenomena, since they occur not only when target and surround are both presented to one eye, but also when the target is presented to one eye and the surround to the other eye.[7] Crowding may be distinguished from contour interaction on the basis of the processing level at which each occurs, with contour interaction involving inhibitory interaction at low level and crowding involving an additional attentional stage.[8] At the fovea, contour interaction and crowding effects are reportedly small[8–10] and, in some conditions, are nonexistent.[11] Hess et al.[12] argued that any crowding at the fovea may be explained in physical terms, whereas Danilova and Bondarko[10] showed, using a range of target and surround combinations, that foveal crowding is likely to be underpinned by a combination of factors, both physical and neural.

The combined effects of interocular differences in stimulus presentation and of spatial proximity have been investigated.[8,13] Meese and Hess[13] found that the effect of interocular interactions on contrast detection depends on whether a peripheral mask is presented dichoptically, half-binocularly or binocularly. (In the dichoptic condition, the test is presented to one eye and the mask to the other eye. In the half-binocular condition, the mask is presented to both eyes, but the test is presented to one eye. In the binocular condition, the test and mask are presented to both eyes.) Using a peripheral dark, thin ring as a mask and a low-spatial-frequency Gabor stimulus as a target, they found contrast threshold to be higher in the dichoptic condition than in monocular viewing. In the half binocular condition, the threshold was found to be at a level between dichoptic and binocular levels. These findings suggest that suppression due to a surround mask is reduced by interocular feature similarities of the mask (half-binocular condition) and further still by interocular feature similarities of the test stimulus (binocular condition).[13] However, it is not known whether interocular similarities of this kind modulate a different process, such as foveal resolution acuity. This question is of interest from a clinical perspective, because resolution acuity is measured clinically with tumbling-E or Landolt C charts. In addition, the impact of interocular similarities on foveal vision is of interest in view of recent developments in vision training, in which binocular viewing systems with foveal targets are presented to one eye, and more peripheral stimuli are presented to the fellow eye or to both eyes.[14–17] Foveal vision in such conditions may be degraded by crowding or contour interaction effects[8] or may be enhanced by interocular similarities of the surround stimuli.[13] However, the impact of interocular similarities in target and surround stimuli on foveal vision in normal observers is not known. The present study addressed this question by measuring foveal resolution acuity in the presence of surround bars presented to the same eye, the fellow eye, or both eyes.

Methods

Subjects

Twenty-two normally sighted adults (12 women, 10 men; mean age, 31.5 years, range 21–38) participated in the study. Each eligible subject signed a statement of informed consent before participating, in accor-

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dance with the Declaration of Helsinki. All subjects had best corrected visual acuity (BCVA) of 0.0 log minimum angle of resolution (logMAR, measured with a Bailey-Lovie chart) or better in each eye, an interocular difference in corrected acuity of <0.1 logMAR units, no manifest strabismus on cover test for near or distance, stereopsis of 40 arc sec or better (Titmus stereotest), and normal ocular health, assessed by direct ophthalmoscopy.

Apparatus

Stimuli were generated with a graphics card (VSG 2/5; Cambridge Research Systems, Rochester, UK) in a host computer. All stimuli were presented at the center of a 20-in. flat fast phosphor monitor (Monoray; Clinton Electronics Corp., Loves Park, IL) with a resolution of 1024 × 769 and dimensions of 2.6° × 1.94° at a viewing distance of 8 m. The monitor was gamma corrected. Liquid crystal shutter goggles were synchronized with the monitor frame rate so that alternate frames were presented independently to each eye. In this way, different images were presented on each frame, and each eye saw only one of these images. The fast phosphor decay time of the monitor minimized crosstalk so that the image on one frame did not persist into the next frame, and no flicker was perceived. The stimulus was presented to each eye at a frame rate of 60 Hz, which was half of the full monitor refresh rate.

The subjects were tested wearing the goggles in all conditions, even if unnecessary (e.g., in the binocular condition), to maintain a constant stimulus luminance level across conditions. The mean luminance level of the stimulus was 51.9 cd/m^2, but it was reduced to 4.5 cd/m^2 when viewed through the goggles and via the mirror (see the Procedure section). The shutter goggles were worn over spectacle correction, if necessary.

Stimuli

Resolution acuity was measured with a Landolt C letter target with four possible gap orientations (right, left, up or down). The Landolt C was constructed as an annulus in a 5 × 5 grid. A gap, one fifth of the dimension of the square grid, was inserted into the annulus in the right, left, top or bottom position. Four tangential bars of width equal to the gap in the C and length equal to its diameter were positioned around the C (Fig. 1). The distance between the Landolt C and bars was 0.4 of the width of the letter.[7,8,18]

The target and surrounding bars were presented at the center of the display at −0.82 Weber contrast. Stimulus duration was brief (142 ms) to minimize any effect of change in fixation during stimulus presentation. In addition to the C (and surround bars), two vertical and two horizontal markers of −0.47 Weber contrast width 0.1° and length 0.6° were presented at 0.8° from fixation. These markers assisted in identifying the fixation point, and served as a check for suppression and fusion, since one vertical and one horizontal marker were presented to each eye. In the absence of suppression, the observer was aware of all four bars. In the absence of fixation disparity during fusion, the vertical and horizontal bars were perceived in alignment. The subjects were asked whether they could perceive both pairs of bars and whether the bars were in alignment before and during each test condition.

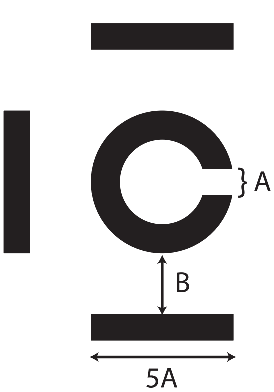

FIGURE 1. Schematic of the stimulus. A, width of the Landolt C gap and flanking bars; B, distance between the Landolt C and the bars.

Procedure

The display was viewed via a front silvered mirror at a distance of 4 m, allowing a viewing distance of 8 m. Room illumination was switched off, and the only source of light was from the monitor. The eye with poorer acuity was designated the test eye to which the target would be presented for acuity measurement in monocular, dichoptic, and half-binocular conditions. For this reason, the monocular condition was applied first, followed in pseudorandom order by the other three conditions. The reason that the eye with poorer acuity was chosen as the test eye was that previous work suggests a more pronounced effect of surround bars when presented to the eye with better resolution acuity.[7]

The following viewing conditions were used in the experiments:

- In the monocular condition, the Landolt C and bars were presented to the test eye, whereas the nontested eye was occluded with a black opaque patch. In a pilot study, no difference was found, whether the nontested eye wore a black patch or viewed a uniform stimulus with the same mean luminance as that of the tested eye.
- In the binocular condition, the Landolt C, and the bars were presented to both eyes.
- In the dichoptic condition, the Landolt C was presented to the test eye, and the bars were presented to the nontested eye.
- In the half-binocular condition, the Landolt C was presented to the test eye, and the bars were presented to both eyes.

Resolution acuity was determined with a single-interval, four-alternative, forced-choice double staircase, with a step size of 0.05 log unit. The size of the Landolt C was varied in a staircase procedure that decreased the target size after two correct responses and increased the size after one incorrect response (two down, one up). The observer's task was to indicate the orientation of the C gap (up, down, right, left) and enter their responses using the corresponding key (up, down, left, or right arrow) on a computer keyboard. The two staircases were visited in random order. The staircases ended after 11 reversals, and the threshold was calculated as the mean of the midpoints of 10 reversals (5 reversals in each staircase). The first of 11 reversals was excluded, to minimize the effect of subject error.

Every response entry was accompanied by an audible tone, but no feedback was given. Observers were given practice runs at a close distance to the monitor while viewing directly, and at 8 m while viewing via the mirror.

The contour interaction effect was tested in a subgroup of 10 of the 22 subjects, to determine whether this effect would be elicited with our foveal stimulus. For this purpose, resolution acuity in monocular and binocular conditions was measured in these subjects with and without the surround bars (flanked and unflanked condition).

Data Analysis

For contour interaction testing, the sample size was relatively small. Thus, the nonparametric Wilcoxon signed rank test was used to determine the difference between resolution acuity measured with and without bars in monocular or binocular conditions.

Data from the full group were normally distributed; thus, a parametric test was used. For comparisons across monocular, binocular, half-binocular, and dichoptic viewing conditions a repeated-measures ANOVA was applied.

RESULTS

Table 1 shows mean logMAR acuity measured in each viewing condition. Note that mean acuities were poorer than the 0.0

Table 1. Group Mean Resolution Acuity Measured under Each Viewing Condition

Viewing Condition	Mean logMAR (95% CI)	Sample Size (n)	Mean Difference (95% CI)
Difference between Binocular and Other Viewing Conditions			
Binocular	0.101 (0.038–0.163)	22	NA
Half-binocular	0.225 (0.143–0.308)	22	0.124 (0.203–0.046)
Monocular	0.242 (0.171–0.314)	22	0.142 (0.199–0.084)
Dichoptic	0.279 (0.186–0.373)	22	0.179 (0.271–0.086)
Difference between Conditions with and without Surround Bars			
Binocular bars	0.151	10	
Binocular no bars	0.135	10	−0.016
Monocular bars	0.199	10	
Monocular no bars	0.179	10	−0.02

A negative value indicates decrement in the condition with surround bars. CI, confidence interval.

level, whereas all subjects showed acuity of 0.0 or better on a logMAR chart. This difference may be due to the relatively low luminance of the stimulus[19] viewed via the goggles and mirror. For the sample of 10 subjects in whom contour interaction effects were investigated, resolution acuity was similar for monocular viewing, with or without surround bars, as well as for binocular viewing, with or without surround bars ($P > 0.1$). This finding indicates that resolution acuity was not significantly affected by contour interaction effects in either monocular or binocular viewing.

In the full group, mean differences in resolution acuity were significantly different across viewing conditions ($P < 0.001$; Table 1). Further analysis using Bonferroni post hoc tests showed that resolution acuity was significantly better in the binocular condition than in the monocular condition ($P < 0.001$), the half-binocular condition ($P = 0.001$), and the dichoptic condition ($P < 0.001$; Fig. 2). Resolution acuity was also significantly better in the half-binocular condition than in the dichoptic condition ($P = 0.029$).

Discussion

The purpose of the present study was to increase understanding of the way in which foveal resolution acuity is affected, if at all, by the interocular similarities of surround stimulus.

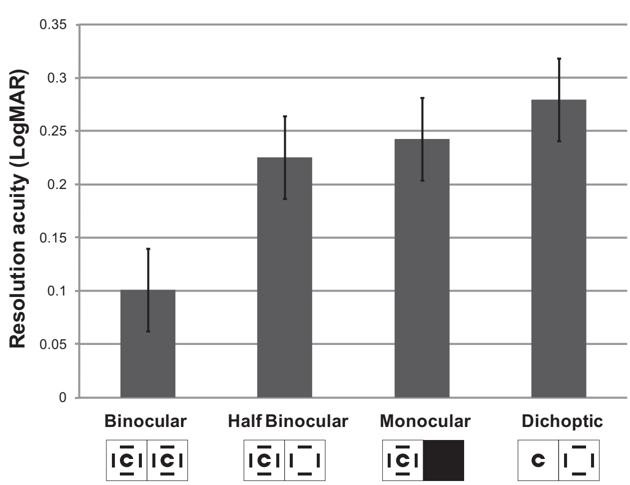

Figure 2. Resolution acuity in a range of viewing conditions. The four conditions are indicated on the x-axis and each condition is illustrated below the axis. The *filled square* in the monocular condition represents an eye patch. The y-axis shows resolution acuity in logMAR. Error bars, 1 SEM.

Binocular versus Monocular, Dichoptic, and Half-Binocular

Our finding that resolution acuity is significantly better in the binocular viewing condition compared with the other three conditions is in agreement with the well-established phenomenon of binocular summation.[2–4]

The present results unexpectedly showed a binocular summation ratio of 1.4 (41.8%) for resolution acuity. This value, although it is larger than the 10% to 11% summation reported in previous studies in high-contrast conditions,[4,20] is in agreement with values observed with low-contrast resolution acuity[20] or contrast detection.[21] The high summation could be due to the simplicity of the task, since more complex tasks have been found to result in lower summation.[1,5] Another possible explanation is that summation was enhanced by the low stimulus luminance in our viewing system.[22]

Monocular versus Dichoptic and Half-Binocular

When the monocular condition was compared with the half-binocular and dichoptic conditions, no significant difference in acuity was observed. These three conditions were similar, in that the target was presented to only one eye; thus, the target itself could not contribute to summation. Results in previous work on contrast detection suggest that a difference could be expected between monocular and dichoptic conditions.[13] On the other hand, Flom et al.[7] found no significant difference between dichoptic and monocular conditions in resolution acuity measured with a target similar to ours, in agreement with the present findings.

This difference between findings in resolution acuity and contrast detection experiments may be due to either the difference between tasks or the magnitude of effect produced by the feature surrounding the central target. In particular, previous studies have suggested that reduction in visual performance during dichoptic presentation may, in part, be due to interocular inhibition,[13,23] which is lower in a visual resolution task than in a detection task.[23]

Dichoptic versus Half-Binocular

Our results show that resolution acuity is significantly poorer in the dichoptic condition than in the half-binocular condition. The difference between these two conditions is that in the half-binocular condition surround bars were presented to both eyes, but in the dichoptic condition, they were presented to the nontested eye only. No inhibitory or excitatory effect of the bars themselves on the acuity was found, since there was no significant difference between acuities with and without the surround bars, in monocular and binocular conditions. In view of this, it seems likely that similarities between the images presented to each eye enhanced visual resolution in the half-binocular compared with the dichoptic condition.

The present findings for resolution acuity are, in part, consistent with those reported by Meese and Hess[13] for contrast threshold. In that study, contrast threshold was higher when a contrast target and a surround mask were presented dichoptically than when presented half-binocularly. They attributed their findings to interocular inhibition in the dichoptic condition and to the release of this inhibition when interocular similarity of the stimuli was increased in the half-binocular condition. Likewise, in the present study, interocular stimulus differences in the dichoptic condition and similarities in the half-binocular condition may explain better acuity in the latter condition.

In the dichoptic condition, the stimulus presented to the nontested eye was at higher space-averaged luminance than in the half-binocular condition. However, it seems unlikely that this difference could explain the threshold differences across these conditions, since the interocular difference in space-averaged luminance did not exceed 0.1 cd/m^2 across those viewing conditions.

Our findings show that resolution acuity was worse when the target and bars were presented dichoptically than when presented in the half-binocular condition. This finding agrees with previous work,[13] showing similar effects with contrast threshold measurements in dichoptic and half-binocular conditions. These findings suggest that interocular interactions observed in resolution acuity have some mechanisms in common with those reported for contrast threshold. In addition, other mechanisms beyond the low-level stages at which interocular inhibitory and summative effects could occur may also be involved. Previous findings indicate that feedback from the extrastriate cortex to V1 plays an important role in feature integration.[24] Higher order processes of this kind could have an impact on interocular interactions for several visual functions, including contrast threshold and resolution acuity.

Taken together with previous findings,[13,25] our data suggest that although the main contribution to binocular enhancement is summation of the target, the similarity of the surround features also contributes to improving the visual resolution.

In the present study, we found that in adults with normal vision, acuity is better in half-binocular viewing than in dichoptic viewing. Although our study did not include subjects with abnormal vision, these findings may have implications for stimuli used in amblyopia therapy. In particular, therapy may involve the presentation of foveal stimuli to the test eye and nonfoveal stimuli to the fellow eye.[14–17] In this method, findings of the present and previous work suggest that visual sensitivity is likely to be enhanced when noncentral stimuli are presented to both eyes. The comparison of dichoptic and half-binocular viewing conditions used in this study is readily amenable to future studies of amblyopic subjects.

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