Orientation Discrimination in Amblyopia

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Using extended sinusoidal gratings to avoid potential problems of eccentric fixation, the authors have studied orientation discrimination in amblyopia. For all subjects, elevated orientation discrimination thresholds at high spatial frequencies were found. However, raised thresholds decrease with decreasing spatial frequency, and can be normal at low frequencies. Orientation discrimination thresholds for both amblyopic and non-amblyopic eyes are independent of contrast over most of the visible range. Therefore, amblyopic orientation discrimination thresholds cannot be mimicked in non-amblyopic eyes by reducing contrast. Control experiments show that the orientation discrimination deficits are not restricted to vertical stimuli and that they are not a result of exaggerated cyclotorsional eye movements. Invest Ophthalmol Vis Sci 27:532–537, 1986

Amblyopia is defined as a condition in which visual acuity is reduced without any apparent cause. Recent studies have shown that amblyopia is associated with a wide variety of visual anomalies. Thresholds for contrast detection, flicker detection, motion detection, spatial frequency discrimination, phase discrimination, and vernier acuity are all elevated in amblyopia. Although a diverse array of anomalies exists, the above studies all show abnormalities with a similar spatial frequency dependence. Deficits are typically largest at high frequencies, decrease as frequency decreases, and are often absent at low spatial frequencies. Because of this frequency dependence, tests of visual functions in amblyopia performed with stimuli that contain multiple frequencies or broad-bands of frequencies are difficult to interpret. With such broad band-stimuli, a deficit restricted to a high-frequency range may be missed if the observer can perform the task effectively with low-frequency information.

Because of this problem, the recent results of Vogels et al, showing almost normal orientation discrimination thresholds for bar stimuli, which contain a broad range of spatial frequencies, are hard to interpret. Orientation discrimination thresholds of normal observers are almost independent of spatial frequency. Therefore, the experiment of Vogels et al does not distinguish between the possibilities of substantial spatial frequency specific orientation discrimination deficits and relatively normal orientation discrimination performance at all spatial frequencies.

There are two additional problems associated with the experimental design of Vogels et al: (1) A single bar may not be imaged foveally in eccentrically fixating amblyopes. Because orientation discrimination thresholds in normal observers may be elevated in the periphery, the small threshold elevations seen by Vogels et al may reflect normally elevated thresholds in peripheral vision. (2) Detection of bar stimuli is impaired in amblyopia. Elevated orientation discrimination thresholds may therefore have resulted from problems in detecting the stimulus.

We have re-examined the question of orientation discrimination in amblyopia. Using sinusoidal gratings as stimuli and by performing control experiments, we have avoided the problems listed above. We find that amblyopia is associated with substantial deficiencies in orientation discrimination that are clearly spatial frequency dependent. The elevated orientation discrimination thresholds are present over a wide range of stimulus contrasts and cannot easily be attributed to eccentric fixation or elevated contrast thresholds.

Materials and Methods

Apparatus

A microprocessor-based stimulus generator was used to create gratings with a sinusoidal luminance profile on the face of a display CRT (Tektronix 606, Tektronix; Beaverton, OR). Space average luminance of the screen was 60 cd/m². The screen was masked down to a 4-degree diameter circle. Grating contrast, spatial frequency and presentation timing were under computer control. Grating orientation was changed by adding to the X-axis half a cycle of a triangular waveform synchronized with the Y-axis sweep. Fine control
Table 1. Clinical data for amblyopic subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Refractive error (diopters)</th>
<th>Visual acuity</th>
<th>Strabismus (prism diopters)</th>
<th>Fixation of amblyopic eye (prism diopters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS</td>
<td>RE -8.50 -1.00 × 5 LE -1.00</td>
<td>20/300</td>
<td>2 ESO</td>
<td>1 N unsteady</td>
</tr>
<tr>
<td>CD</td>
<td>RE +3.00 LE +6.75 -2.00 × 85</td>
<td>20/15</td>
<td>24 EXO</td>
<td>3 ST unsteady</td>
</tr>
<tr>
<td>CW</td>
<td>RE +2.00 LE PLANO</td>
<td>20/40</td>
<td>8 EXO</td>
<td>1/2 T unsteady</td>
</tr>
<tr>
<td>EB</td>
<td>RE -5.00 LE +2.00 -1.00 × 50</td>
<td>20/20</td>
<td>12 ESO</td>
<td>2 N unsteady</td>
</tr>
<tr>
<td>DM</td>
<td>RE +1.75 -0.25 × 120 LE +2.50</td>
<td>20/15</td>
<td>10 ESO</td>
<td>2 N unsteady</td>
</tr>
<tr>
<td>JM</td>
<td>RE +1.50 -0.50 × 88 LE +0.75</td>
<td>20/25</td>
<td>2 ESO alt</td>
<td>1/2 SN steady</td>
</tr>
<tr>
<td>CS</td>
<td>RE +1.75 -0.75 × 89 LE +1.00 -0.50 × 98</td>
<td>20/20+</td>
<td>21 ESO</td>
<td>na</td>
</tr>
</tbody>
</table>

Clinical examination data for 7 amblyopes. Abbreviations: N = nasal, T = temporal, S = superior, na = data not available, ESO = esotropia, EXO = exotropia, alt = alternating, LE = left eye, and RE = right eye.

of orientation was achieved by attenuating the triangular wave in 0.1 log unit steps. Therefore, for a 1-degree orientation difference, the step size (average of upward and downward steps) was 0.23 degrees, for a 0.5 degree difference step size was 0.12 degrees, etc.

A separate stimulus was created by use of a full cycle of the triangular wave. This target, a chevron (depicted schematically in Fig. 6), was also used to measure orientation discrimination.

Procedure

Monocular contrast sensitivity measurements were made using a temporal two-alternative forced choice (2AFC) staircase technique (3 correct responses—step down, one incorrect response—step up; this staircase asymptotes at the 79% correct level\(^\text{14}\)). Subjects pressed one of two buttons to identify which interval contained the grating. Contrast was varied in 0.1 log unit steps and means of the last 5 of 7 staircase reversals were used as threshold estimates.

Orientation discrimination thresholds for gratings were determined monocularly using the same staircase procedure. Two gratings were presented sequentially for 500 msec. The presentations were separated by a 500-msec period during which the screen was blank and had the same space average luminance as the gratings. Gratings were matched for contrast and spatial frequency. One stimulus of each pair was always oriented at a given reference (eg, vertical). The second stimulus was either (1) a grating tilted clockwise with respect to the reference, or (2) a chevron with gratings in the top and bottom halves tilted symmetrically about that of the reference. The order of presentation was randomized, and the subject indicated which of the two presentations contained the tilted grating.

Subjects

Seven subjects were used who had varying degrees of amblyopia associated with anisometropia, strabismus, or both. Complete refractive data, determined from clinical examinations, are shown in Table 1. All subjects were tested while wearing their appropriate corrective lenses. Complete sets of data could not be obtained for all observers; Contrast sensitivity data were not obtained for JM, and orientation discrimination versus contrast functions were not obtained for CD. Control experiments with oblique and chevron stimuli were performed with only 2 and 3 observers, respectively. Informed consent was obtained from each observer prior to his (or her) participation.

Results

We first measured contrast sensitivity functions of 6 amblyopes (EB, CD, CS, DM, CW, RS). These data are shown in rows 1 and 3 of Figure 1. A comparison of data from different observers reveals a common pattern. At high spatial frequencies contrast sensitivity is lower for amblyopic (open symbols) than for non-amblyopic (filled symbols) eyes. However, as spatial frequency is reduced, the difference between the two eyes decreases until, at the lowest frequencies (eg, 5.0 c/deg), both eyes exhibit similar sensitivities. All six observers show this type of contrast sensitivity deficit, which is typical of amblyopes with anisometropia\(^\text{15}\) and strabismus.\(^2\)
We determined orientation discrimination thresholds for the same six observers over the same range of spatial frequencies. These results, obtained with vertical gratings of 50% contrast, are shown in rows 2 and 4 of Figure 1. Thresholds for the non-amblyopic eyes (filled symbols) are similar to those reported for normal observers. There are no clear changes in discrimination threshold with spatial frequency for the non-amblyopic eyes although thresholds for higher frequencies tend to be a little lower. Lowest thresholds are generally between 0.5 and 1 degree, which are slightly higher than thresholds for experienced observers. However, this may be attributed to using unpracticed observers and monocular testing; binocular viewing appears to produce lower discrimination thresholds. We conducted cursory tests using normal subjects and found that monocular orientation discrimination thresholds were approximately 25% higher than binocular thresholds.

Data for the amblyopic eyes (Fig. 1, open circles) differ from those for the non-amblyopic eyes. For each observer, thresholds increase with spatial frequency. Four subjects (CS, DM, CW, and RS) show a similar pattern. Orientation discrimination thresholds are similar for both eyes at the lowest spatial frequencies, but at higher frequencies, thresholds for the amblyopic eyes increase up to 3-5 degrees. Two subjects (EB, CD) show a somewhat different pattern. In both cases orientation discrimination thresholds are elevated at the lowest spatial frequency (0.5 c/deg), but these amblyopes also show additional threshold increases at higher frequencies. The results demonstrate that impairment of orientation discrimination in amblyopia shows a spatial frequency dependency similar to other visual deficits. An extreme case of a spatial frequency dependent orientation discrimination deficit was demonstrated by an additional observer (JM), for whom contrast sensitivity data were not obtained. This subject showed equal thresholds of approximately 1 degree for both eyes between 1 and 10 c/deg, but thresholds for the amblyopic eye increased up to 5 degrees. Two subjects (EB, CD) show a somewhat different pattern. In both cases orientation discrimination thresholds are elevated at the lowest spatial frequency (0.5 c/deg), but these amblyopes also show additional threshold increases at higher frequencies. The results demonstrate that impairment of orientation discrimination in amblyopia shows a spatial frequency dependency similar to other visual deficits. An extreme case of a spatial frequency dependent orientation discrimination deficit was demonstrated by an additional observer (JM), for whom contrast sensitivity data were not obtained. This subject showed equal thresholds of approximately 1 degree for both eyes between 1 and 10 c/deg, but thresholds for the amblyopic eye increased abruptly near 14 c/deg (Fig. 2). Closer examination of the spatial frequency range from 10 to 17 c/deg (inset) shows that there was a continuous change in threshold from 1 to 5.5 degrees over this range of spatial frequencies.
Fig. 3. Interocular threshold ratios (amblyopic/non-amblyopic) for orientation discrimination (open symbols) and contrast sensitivity (filled symbols) are plotted against spatial frequency (cycles/degree). Dashed lines indicate no interocular threshold difference.

Although contrast sensitivity and orientation discrimination thresholds are affected quite differently by spatial frequency in normal observers, the relation between the amblyopic and non-amblyopic eyes shows certain similarities between the two experiments. In order to quantitatively compare the effects of spatial frequency on both contrast sensitivity and orientation discrimination, we have plotted interocular threshold ratios (amblyopic eye/non-amblyopic eye) for both sets of data as a function of spatial frequency (Fig. 3). Both ratios increase with frequency for all six amblyopes, and those amblyopes with large contrast sensitivity deficits tend to exhibit the largest orientation discrimination deficits.

The results (Figs. 1–3) show that large spatial frequency specific orientation discrimination deficits exist in amblyopia. In the next section of this report, we examine possible sources of these deficits. Our use of extended gratings makes small eccentric fixation anomalies an unlikely cause of the elevated discrimination thresholds. However, the similarity between contrast sensitivity and orientation discrimination deficits suggests a possible connection. The elevated orientation discrimination thresholds may be a direct result of elevated contrast detection thresholds. That is, even though the contrast of a suprathreshold grating may be closer to the amblyopic than the non-amblyopic contrast threshold, this cannot account for the elevated orientation discrimination thresholds. This experiment demonstrates that spatial frequency specific orientation discrimination deficits in amblyopia cannot be directly attributed to reduced contrast sensitivity.
We considered two other possible explanations for our results. All orientation discrimination thresholds described above were determined with vertical reference stimuli. Normal observers show elevated orientation discrimination thresholds with oblique reference stimuli.\(^9\) These elevated thresholds are present over the entire range of visible contrasts and increase with spatial frequency. It is possible, therefore, that the amblyopic elevated thresholds simply reflect normal performance for oblique stimuli even though the gratings were vertical. One possible explanation for improved performance with vertical stimuli for normal subjects is that some extraneous information may be utilized, e.g., an “internal vertical reference” or vestibular cues.\(^19\) The elevated amblyopic orientation discrimination thresholds found with vertical gratings may, therefore, reflect a failure to integrate this extraneous information with visual input received through the amblyopic eye.

In order to examine this possibility, we tested orientation discrimination as a function of contrast for an oblique reference. Results for two observers (RS, DM) are shown in Figure 5. Except for an overall increase in thresholds for both eyes, the data are similar to the results obtained with vertical stimuli. Amblyopes exhibit higher thresholds at all contrast levels. Therefore, as was shown above with vertical stimuli, elevated thresholds at oblique orientations cannot simply reflect impaired contrast sensitivity. The results show that reduced orientation discrimination in amblyopia is not just a selective loss of fine orientation discrimination for vertical stimuli.

We examined a second possible explanation for our results. During attempted monocular fixation, amblyopes exhibit abnormally large drifts\(^20\) and saccades.\(^21\) We considered the possibility that, in addition to their documented abnormal eye movements, amblyopes have exaggerated cyclotorsional fluctuations. Such abnormal eye movements could provide a particular problem for orientation discrimination when the task involves two stimuli separated in time (as in our temporal 2AFC procedure). Orientation differences in the retinal image between the two presentations could be due to torsional eye movements that occurred in the interval separating the presentations of the two stimuli in addition to orientation differences in the stimulus. In an attempt to avoid this potential problem we re-examined orientation discrimination using a chevron stimulus. In this experiment the task was to identify which interval contained the chevron (see inset of Fig. 6). Because the two orientations to be discriminated are now presented simultaneously, i.e., upper and lower portions of the chevron, this experiment is unlikely to be affected by abnormal cyclotorsional eye movements.
occuring between presentations. Such eye movements would not affect orientation differences between the two halves of the chevron. We tested orientation discrimination in this way as a function of contrast for three amblyopes (RS, CW, and DM). The data, plotted in Figure 6, show the same qualitative pattern previously found with the standard orientation experiment (ie, Figs. 4–5). Orientation discrimination thresholds for amblyopes are elevated at all contrasts. Interestingly, two of the subjects (RS and CW) exhibited larger interocular differences with the chevron test than with the original orientation discrimination experiment (Fig. 1). The source of these differences is unknown, but the elevated orientation discrimination thresholds with chevrons suggest that abnormal cyclotorsional eye movements are not the cause of the elevated orientation discrimination thresholds found in amblyopia. In addition, because orientation discrimination thresholds obtained with chevron stimuli show the same contrast independence as seen above for parallel gratings, these elevated amblyopic thresholds are not due to contrast sensitivity deficits.

Discussion

We have shown that orientation discrimination thresholds for amblyopes can be normal or abnormal depending on the spatial frequency content of the stimulus. This finding is consistent with previous suprathreshold studies of contrast,22 phase,6 and spatial frequency discrimination,23 in that visual performance for suprathreshold gratings tends to be impaired selectively in amblyopia at middle and higher spatial frequencies. Our data are not attributable to exaggerated torsional eye movements (Fig. 6), or an absence of the very fine thresholds for vertical gratings (Fig. 5). Unlike amblyopic vernier acuity thresholds,7 our results cannot be attributed to elevated contrast detection thresholds. In contrast to the present data obtained at medium and high spatial frequencies, Vogels et al.8 using bar stimuli, found only small increases in orientation discrimination in amblyopic observers. Because orientation discrimination typically is near normal for low spatial frequencies, it is possible that the amblyopes in their study used the low-frequency components of the bars to perform the orientation discrimination task. The present finding of spatial frequency specific orientation discrimination deficits serves to emphasize the importance of using narrow-band stimuli when testing visual functions in amblyopia.

Key words: amblyopia, orientation discrimination, contrast sensitivity

References