Orientation variance discrimination in amblyopia

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Our previous results showed that while amblyopes can efficiently integrate visual signals, they are poor at segregating signals in noise. This could be either because integration detectors have broader bandwidths or because of a selective extrastriate segregation anomaly. One consequence of the former would be poorer variance discrimination. Using a two-alternative forced-choice paradigm, observers were asked to judge the orientational variance for arrays of 16 Gabors. All observers, be they normal or amblyopic, could perform the task similarly, although at high spatial frequencies, amblyopic eyes needed slightly more incremental variance than the normal eyes. We conclude that normals and amblyopes integrate signals in a similar way. © 2007 Optical Society of America

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1. INTRODUCTION

We have recently shown that amblyopes are specifically poor at tasks in which signals need to be discriminated within a noisy environment. This has been shown for tasks in which judgement of the orientation or motion direction of signal elements embedded in a field of randomly oriented or randomly moving elements has to be made [1,2]. We have also shown this for tasks in which subjects are asked to judge the mean orientation or motion direction of an array of elements embedded in a field of either randomly oriented or randomly moving elements [3]. Since we had previously shown that in the absence of noise, amblyopes can integrate both local orientation [4] and local motion [5] signals normally, we interpreted this abnormality when noise is present as being due to an inability to segregate the signal from the noise in such tasks. Such an abnormality being global in nature would most likely be located in the extrastriate cortex, where the receptive fields are larger [6] and where lesion studies in animals [7] and man [8] have shown such global processing occurs.

We do not believe that broader orientational tuning properties of individual cells in V1, which are driven by the amblyopic eye (AME), can represent an explanation because we set out to equate performance at the single-element level before undertaking the global integration task. However, it is possible that an explanation could be couched in terms of broader tuning properties of extrastriate cells responsible for global integration. The consequence would be just as good integration (for example across orientation or across motion direction) but poorer segregation, similar to what we have reported in amblyopia [3]. However, an inevitable side effect of more broadly tuned detectors responsible for integration would be poorer variance discrimination, resulting from the more extensive integration. This offers a way of assessing whether the previous results indicating normal integration but poorer segregation are better explained by an abnormality involving the broadening of the integration bandwidth of extrastriate detectors or whether it is necessary to posit an extrastriate abnormality involving segregative processing per se. We therefore undertook a study of orientation variance discrimination in a group of amblyopic observers who had previously demonstrated the combined effects of normal integration but poorer segregation for this particular global task. The results suggest that while there may be a subtle anomaly for variance discrimination at high spatial frequencies, the performance of amblyopes on this type of task is similar to that of normals.

2. METHODS

A. Observers
Nine normal and nine amblyopic observers were recruited for this experiment. One of the normal observers was the author. The others were naïve to the purpose of the experiment. All observers were optically corrected if necessary. Clinical details of amblyopic observers are presented in Table 1.

B. Apparatus
We used an Apple Macintosh G3 computer with the MATLAB environment (MathWorks Ltd.) and the PSYCHOPHYSICS TOOLBOX package [9]. All stimuli were displayed on a 20 in. Sony monitor (Trinitron 520 GS), which was calibrated and linearized using a Graseby S370 photometer and the VIDEO TOOLBOX [10] package. Pseudo-12-bit contrast accuracy was achieved by using a video attenuator [11], which combined the RBG outputs of the graphic card (ATI Rage 128) into the G gun. The monitor had a refresh rate of 75 Hz. The mean luminance of the screen...
was 33 cd/m², and the resolution was 1152 × 870 pixels. One pixel on the screen was 0.32 mm, which was 2.12 arc min of the observers' visual angle from the viewing distance of 52 cm. The observers performed the task monococularly, beginning with the fellow fixing eye (FFE) (in amblyopes) and the dominant eye (DE) (in normals), with the other eye patched.

C. Stimuli
The stimuli were arrays of Gabor micropatterns presented on a mean luminance background. The envelope of the Gabor had a standard deviation of 0.4°. The spatial frequency of the sinusoidal modulation within the Gabor was varied between 0.52 cycles per degree (cpd) and 4.16 cpd, depending on the experiment. The Gabors were randomly distributed in a 6° wide circular area. The center of the distribution was the center of the screen. The orientation in each Gabor micropattern was selected from a Gaussian distribution with a variable mean and a predefined bandwidth. The distribution's variance was varied from 0° (all elements aligned) to 784° (high orientation variability) as shown in Fig. 1.

D. Psychophysics
1. Equating Orientation Discrimination Performance for Isolated Stimuli
In order to equate the performance levels for this task for an individual Gabor for FFEs and AMEs, we measured the orientation discrimination threshold for a single Gabor, of the exact type used in the later variance discrimination experiment, as a function of the contrast of the Gabor as described in Mansouri et al. [4]. Although this means that the contrast of stimuli shown to the AME was usually higher than that shown to the FFE, this difference in itself is not important for two reasons. First, in amblyopia, contrast is perceived veridically above threshold [12]. Second, the only relevant measure for which to equate performance in this study is orientation discrimination at the local, single-element level. For some observers (RB, PH, GN, LN, and MA), we used data already collected for another experiment [4]. The single Gabor was presented in a random position within the 6° stimulus area and was tilted clockwise or counterclockwise from vertical. The observers' orientation threshold was estimated as the slope of the best-fitting cumulative Gaussian psychometric function derived from between 192 and 340 presentations. We estimated 95% confidence intervals from 1000 bootstrap replications of the fit [14]. For the amblyopic observers, the single Gabor was presented to the AME with a fixed high contrast (75%) and to the FFE with a range of contrasts. The threshold for the FFE increased with decreasing contrast. Therefore, the contrast with which the FFE gave threshold for orientation discrimination equal to that of the AME (having a contrast of

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**Table 1. Clinical Details of Amblyopic Observers Participating in the Experiment**

<table>
<thead>
<tr>
<th>Observers</th>
<th>Age(yr)/Sex</th>
<th>Type</th>
<th>Refraction</th>
<th>Acuity</th>
<th>CS% at 0.5 cpd</th>
<th>CS% at 1 cpd</th>
<th>Squint</th>
<th>History</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN</td>
<td>30/M</td>
<td>RE mixed</td>
<td>+5.00–2.00</td>
<td>120°</td>
<td>22.5</td>
<td>4.3</td>
<td>2.8</td>
<td>ET 8° Detected age 5 yr, patching for 3 m, no glasses, 2 surgery RE 10–12 yr</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>+3.50–1.00</td>
<td>75°</td>
<td>28.4</td>
<td>1.6</td>
<td>2.1</td>
<td>ET 6° Detected age 5 yr, patching for 2 yr</td>
</tr>
<tr>
<td>ML</td>
<td>20/F</td>
<td>RE mixed</td>
<td>+1.0–0.75</td>
<td>90°</td>
<td>31.2</td>
<td>2.0</td>
<td>1.6</td>
<td>ET 15° Detected age 13 yr, no treatment</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>−3.25</td>
<td>20/25</td>
<td>37.2</td>
<td>1.8</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>XL</td>
<td>31/F</td>
<td>RE strab</td>
<td>−2.50</td>
<td>20/25</td>
<td>31.9</td>
<td>1.3</td>
<td>1.5</td>
<td>ET 5° Detected age 4 yr, patching for 6 m, surgery age 5 yr</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>−2.75+0.75</td>
<td>20/400</td>
<td>11.3</td>
<td>2.3</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>PH</td>
<td>33/M</td>
<td>RE strab</td>
<td>−2.0+0.50</td>
<td>20/25</td>
<td>33.9</td>
<td>2.6</td>
<td>1.1</td>
<td>ET 5° Detected age 4 yr, patching for 6 m, surgery age 5 yr</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>+0.50</td>
<td>20/63</td>
<td>30.0</td>
<td>2.1</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>RB</td>
<td>49/RE</td>
<td>LE strab</td>
<td>+4.75–0.75</td>
<td>45°</td>
<td>32.5</td>
<td>1.0</td>
<td>2.8</td>
<td>ET 5° Detected age 6 yr, patching for 1 yr</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>+4.75–0.75</td>
<td>20/40</td>
<td>32.5</td>
<td>1.0</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>ED</td>
<td>43/F</td>
<td>LE strab</td>
<td>+0.5</td>
<td>20/15</td>
<td>46.5</td>
<td>1.3</td>
<td>1.8</td>
<td>XT 5° Detected age 6 yr, glasses, near normal local stereo vision</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>+0.5</td>
<td>20/15</td>
<td>46.5</td>
<td>1.3</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>AG</td>
<td>46/M</td>
<td>LE strab</td>
<td>+0.75</td>
<td>20/400</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ET 5° Detected age 3 yr, patching for 3 m, no surgery, no stereovision</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>+0.75</td>
<td>20/20</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>LN</td>
<td>49/F</td>
<td>LE strab</td>
<td>+3.75–3.75</td>
<td>20/30</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>ET 10° Detected age 3 yr, glasses since, patching for 6 m, surgery RE age 20 yr</td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>+3.75–3.75</td>
<td>20/30</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>MA</td>
<td>22/RE</td>
<td>LE strab</td>
<td>−3.00–2.00</td>
<td>80°</td>
<td>20/20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>−3.00–2.00</td>
<td>20/20</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Ortho Detected age 3 yr, patching for 4 yr, glasses for 8 yr</td>
</tr>
<tr>
<td>MA</td>
<td></td>
<td>LE aniso</td>
<td>+3.50–0.50</td>
<td>0°</td>
<td>20/200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LE</td>
<td></td>
<td></td>
<td>+3.50–0.50</td>
<td>0°</td>
<td>20/200</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The following abbreviations are used: strab, strabismus; aniso, anisometrope; RE, right eye; LE, left eye; ET, esotropia; XT, exotropia; ortho, orthotropic alignment; DS, diopter sphere; GA, grating acuity; CS%, contrast sensitivity threshold (percent).
75%) was selected. In the subsequent variance discrimination experiment, the stimuli were presented with the adjusted contrasts for the FFEs and with 75% contrast for the AMEs. This task was performed with all amblyopic observers with stimuli at all spatial frequencies tested in order to find the matching contrast for the FFE of each observer in each condition.

For our group of normal controls, we used stimuli of 25% contrast in the following experiments. This contrast represents the average contrast level used for the FFEs of amblyopes.

2. Variance Discrimination

Arrays of randomly positioned and oriented Gabors were presented. The orientation of an individual array element was chosen from a Gaussian distribution (Fig. 1). A two-interval two-alternative forced-choice paradigm was used. The observers’ task was to judge whether the array presented in the first or second presentation was orientationally more varied (see Fig. 1). The first stimulus interval was for 500 ms, followed by 500 ms of mean luminance background, and then a second stimulus interval was presented for 500 ms. Orientation variance discrimination thresholds were obtained from between 192 and 340 presentations for each of a number of variances of the parent distribution. The orientation variance threshold for each level of variability of the parent distribution was estimated as the slope of the best-fitting cumulative Gaussian function using a maximum-likelihood procedure.

3. Variance Discrimination within Different Spatial Frequency Bands

In the first experiment low-spatial-frequency stimuli (0.52 cpd), which were well within the acuity limit of all observers, were tested in nine amblyopic and nine normal observers.

Since contrast sensitivity is similar to normal in the majority of amblyopes for low spatial frequencies [15], these stimuli are useful because the integration functions of the amblyopic and normal eyes are obtained for a stimulus for which contrast thresholds are normal or only minimally affected. In order to better understand the influences of different spatial frequencies on orientation variance discrimination for the amblyopic visual system, five amblyopic (ED, LN, RB, MA, and PH; see Table 1) and five normal observers were tested with high-spatial-frequency Gabor arrays. The spatial frequency of the high-frequency stimulus was a factor of 2 below the highest spatial frequency that the observers reported that they could see. The average high-spatial-frequency stimuli were about a factor of 6–8 (3.12–4.16 cpd) above the low-frequency stimuli (0.52 cpd). These were stimuli for which contrast thresholds were elevated in AMEs.

Fig. 1. Examples of stimuli; Arrays of 16 randomly placed and oriented Gabor elements (I–P) were used. Each Gabor is a sample from a Gaussian distribution (A–H), where the average orientations of the distributions were chosen randomly from trial to trial. Eight different pedestal variances were tested (1°–784°).
3. RESULTS

A. Equating Orientation Performance Levels

Figure 2 shows the relationship between the orientation discrimination threshold for a single Gabor and the contrast for one amblyopic observer. Performance is relatively constant at high contrasts but deteriorates as the contrast is reduced [16]. The filled symbol represents the orientation discrimination performance of the AME for a fixed 75% contrast stimulus. The open symbols and dotted curve represent the performance of the FFE as a function of stimulus contrast. In this case, to equate performance levels for the single element, the contrast of the stimuli for the FFE needs to be reduced approximately 10 times (i.e., 7%) of that seen by the AME. We repeated these measurements for all amblyopic observers and used the appropriate contrast for the FFE that equated orientation discrimination performance to that of the 75% contrast stimuli seen by the AME.

The matched contrast for low- and high-spatial-frequency conditions for the FFE are presented in Fig. 3. The average contrasts that were used in the FFE of amblyopic observers are very close to the 25% contrast that was used in normal observers. For PH, the FFE showed the same performance as the AME at 75% contrast, so both eyes were tested at 75% contrast. However, for others this was not the case. The FFEs in XL and AG showed a performance similar to that of the AME when the stimuli were presented to them at very low contrast (i.e., 5%) compared with that of the AME (i.e., 75%).

B. Variance Discrimination

1. Low-Spatial-Frequency Condition

Figure 4 shows the average increment variance thresholds for amblyopic and normal observers. The X axis represents the variance pedestal on a log scale. The Y axis shows the increment variance threshold on a linear scale. The black open squares and dashed curve represent the data from the FFE of the amblyopic observers. The black filled squares and solid curve represent the data from the AMEs of amblyopic observers. The gray filled circles and dashed curve represent the data from the DE on normal observers. The gray open circles and solid curve represent the data from the nondominant eye (NDE) of normal observers. The dashed line represents the results expected from an ideal observer that simply compares profiles of activity from a set of match filters, whose absolute sensitivity has been arbitrarily set.

As the pedestal variance increases, the increment thresholds are almost constant up to the variance of 16°, as one would expect from an ideal observer model. However, incremental sensitivity increases dramatically in all amblyopic and nonamblyopic eyes at larger pedestal values, an aspect not captured by the ideal observer model. However, in normal observers’ eyes, the thresholds first decrease (e.g., from an average of 3.94° at 0° variance to an average of 2.54° at 4° variance in NDE) and then increase (i.e., dipper function). Although this effect was not statistically significant, it was consistent in all normal eyes. The data from the amblyopic observer’s eyes (AME, FFE) did not show the same effect.

Fig. 2. Equating performance for single elements. Orientation discrimination thresholds measured as a function of contrast for a single Gabor element. The results are shown for one amblyopic observer in whom the performance of the amblyopic eye (AME) is fixed at a high contrast (75%) and the performance of the fellow fixing eye (FFE) is measured as a function of contrast. In this case, to equate performance for the AME viewing a 75% contrast stimulus, we used a 7% contrast stimulus for the FFE. Error bars, 95% confidence intervals (CIs).

Fig. 3. Matched contrasts used for the FFEs of amblyopic observers for low- and high-spatial-frequency conditions. AMEs were always tested at 75% contrast. The thick dashed lined represents 25% contrast (used for normal observers).

Fig. 4. Variance discrimination thresholds for amblyopic subjects (dashed curve and open squares for FFEs, and solid curve and closed squares for AMEs) and normal subjects (closed circles and dashed curve for dominant eyes (DEs) and open circles and solid curve for nondominant eyes (NDEs)) for low-spatial-frequency condition. Error bars represent ±0.5 standard deviations. The performances of the four AME, FFE, DE, and NDE are similar across various variances. The horizontal dashed line represents the results from an ideal observer.
The differences are not statistically significant.

FFE are slightly higher, especially at low variances. However, the thresholds for AMEs and NDEs for the high-spatial-frequency condition. Error bars represent ±0.5 standard deviations. The thresholds for AMEs and FFE are slightly higher, especially at low variances. However, the differences are not statistically significant.

2. High-Spatial-Frequency Condition

The highest spatial frequencies at which the amblyopic and the normal observers could perform the variance discrimination task were on average lower than the highest spatial frequency at which they could perform the mean orientation experiment [4] or single-element orientation discrimination (see Methods). This effect was more prominent in amblyopes. The highest spatial frequency at which five amblyopic observers could perform the task are presented in Fig. 5. The average spatial frequency in normal observers is presented as the thick dashed line. As is expected, the highest spatial frequencies in AMEs are smaller than the average spatial frequency in normals.

In Fig. 6 the increment variance thresholds versus the pedestal variance are presented. The black open squares and dashed curve represent the data from the FFE of the amblyopic observers. The black filled squares and solid curve represent the data from the AMEs of amblyopic observers. The gray filled circles and dashed curve represent the data from the DE of normal observers. The gray open squares and solid curve represent the data from the NDE of normal observers.

In the high-spatial-frequency condition, the thresholds start rising at lower pedestal variances (i.e., 4°) compared with the low-spatial-frequency condition (i.e., 16°). The dipper function for normal eyes in the low-frequency condition is not replicated. The average thresholds of AMEs at high spatial frequencies (which are similar to the AME threshold at low spatial frequencies) are slightly higher than the average thresholds of normal observers' eyes (which are lower than their thresholds at low spatial frequencies). The amblyopic thresholds at high spatial frequencies remain higher across the different variances. The FFE thresholds begin at the same level as the threshold for AMEs but are constant up to the 16° of variance, where they catch up with the thresholds for the normal observers' eyes. The thresholds from the NDE are lower than those of the DE, FFE, and AME in the very-high-variance condition (i.e., more than 144°).

4. DISCUSSION

Normal observers require proportionally larger changes in variance as pedestal variance increases, a typical Weber response. This would not be expected from any ideal observer model that simply compared profiles of activity produced by a population of match filters transducing our element arrays. For some reason the human visual system's performance is directly related to the absolute variance of arrays of oriented elements. One possibility is that the introduction of more oblique orientations may add a disproportionate amount of noise to the comparison stage either because of the poorer discrimination of individual elements [17] or because of some higher-level grouping operation.

One surprising result from this study is that amblyopes can discriminate orientational variance with near-normal sensitivity. This would not be expected if their extrastriate integration detectors were much broader in bandwidth, which is one possible explanation for the problems amblyopes have in tasks containing signal and noise [2,3]. On the basis of this, we conclude that it is unlikely that the integration bandwidths of extrastriate detectors are broader in amblyopia. Although the available evidence favors the orientation bandwidth of individual low-level detectors (i.e., V1) being normal in amblyopia [18–20], our method of equating orientation performance at the single-element level was designed to factor out even a small residual low-level difference. Therefore the problems amblyopes have in processing orientational signals when these signals are embedded in orientational noise [3] cannot be due simply to excessive integration. We speculate that, since signal integration is normal in amblyopia, given the well-documented anomaly for global motion processing [1], signal segregation may be selectively affected.

The role of orientation processing in amblyopia is a somewhat confusing area because of a number of apparently conflicting findings. Initially, it was found that the orientation masking functions are normal in amblyopia [18]. Later, it was reported that orientation discrimination was abnormal in amblyopia both for full-field grating
stimuli [21–23] and for Gabor arrays [24]. More recently, we have shown normal integration [4,5] in amblyopia but abnormal orientation signal/noise discrimination [3]. Finally, it has been proposed [25] that neural errors in orientation coding in V1 may account for the nonveridical perceptions experienced by amblyopes [26]. Three points should be kept in mind: First, there is no compelling support for the bandwidth of individual detectors being broader in amblyopia; in fact, even the study that showed abnormal discrimination [24] argues against this. Second, the study that does show that discrimination is abnormal also shows that it is strongly contrast dependent, a fact used by later integration studies [4] to equate performance at the single-element level. Thus abnormal discrimination at the local level is not inconsistent with the later integration of orientation being normal [4,5]. Third, if the nonveridical perceptions that are experienced by amblyopes are due to errors in neural coding at an early cortical level, then these signals must not drive the mechanisms responsible for the variance discrimination (that we report here is normal in amblyopia). If it did, one would have expected it to contribute additional variability (a neural pedestal adding to the stimulus pedestal), and as a consequence the amblyopic variance discrimination function would be displaced to the left.

There is a suggestion in the data that variance discrimination might be subtly different in amblyopes compared with normals. First, the very small “dipper” effect seen in normal observers at low spatial frequencies was not observed in our amblyopic participants. Second, at spatial frequencies close to the limit of the AME, variance discrimination is subtly elevated. Neither of these effects was statistically significant in the present study, but they were consistent.

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