Nonveridical Visual Perception in Human Amblyopia

Brendan T. Barrett,1 Ian E. Pacey,1 Arthur Bradley,2 Larry N. Thibos,2 and Paul Morrill3

PURPOSE. Amblyopia is a developmental disorder of spatial vision. There is evidence to suggest that some amblyopes misperceive spatial structure when viewing with the affected eye. However, there are few examples of these perceptual errors in the literature. This study was an investigation of the prevalence and nature of misperceptions in human amblyopia.

METHODS. Thirty amblyopes with strabismus and/or anisometropia participated in the study. Subjects viewed sinusoidal gratings of various spatial frequencies, orientations, and contrasts. After interocular comparison, subjects sketched the subjective appearance of those stimuli that had nonveridical appearances.

RESULTS. Nonveridical visual perception was revealed in 20 amblyopes (~67%). In some subjects, misperceptions were present despite the absence of a deficit in contrast sensitivity. The presence of distortions was not simply linked to the depth of amblyopia, and anisometropes were affected as well as those with strabismus. In most cases, these spatial distortions arose at spatial frequencies far below the contrast detection acuity cutoff. Errors in perception became more severe at higher spatial frequencies, with low spatial frequencies being mostly perceived veridically. The prevalence and severity of misperceptions were frequently found to depend on the orientation of the grating used in the test, with horizontal orientations typically less affected than other orientations. Contrast had a much smaller effect on misperceptions, although there were cases in which severity was greater at higher contrasts.

CONCLUSIONS. Many types of misperceptions documented in the present study have appeared in previous investigations. This suggests that the wide range of distortions previously reported reflect genuine intersubject differences. It is proposed that nonveridical perception in human amblyopia has its origins in errors in the neural coding of orientation in primary visual cortex. (Invest Ophthalmol Vis Sci. 2003;44:1555–1567) DOI: 10.1167/iovs.02-0515

Amblyopia is a developmental disorder of spatial vision resulting in reduced visual function, despite good retinal image quality and the absence of overt disease in the eye or visual system. The condition is normally uniorcular, affects 2% to 5% of the population, and is almost always associated with a history of strabismus, anisometropia, or form deprivation in early life.1,2 In addition to reduced visual acuity, most amblyopes exhibit a diminished sensitivity to contrast at high and medium spatial frequencies,3–8 paralleling those seen with simple low-pass filtering.9 It is clear, however, that amblyopic central vision is not simply a low-passed version of normal foveal vision. Instead, several reports have shown significant parallels between the central vision of amblyopes and normal peripheral vision.10 For example, in both cases, positional sensitivity is significantly degraded.11,12 Furthermore, suprathreshold perceived contrast13 and suprathreshold contrast discrimination14,15 are normal in amblyopic central vision and normal peripheral vision.

Although most of the experimental literature on human amblyopia has concentrated on defining the threshold for visual stimuli (e.g., smallest letter, lowest contrast, smallest positional offset), striking features of amblyopic vision occur also in the suprathreshold domain of clearly visible targets. Distorted perception in human amblyopia was first described in detail by Pugh16 who asked amblyopes to describe the appearance of high-contrast letters. These typically subtle distortions are minor compared with the perceptual errors that have been reported by other investigators when amblyopes have been asked to draw spatially localized stimuli17 or sinusoidal grating targets.18–20

Three distinctly different hypotheses have been developed to explain amblyopic visual deficits. Hess et al.,18 who first described distorted perception of gratings in amblyopia, developed a neural scrambling model21,22 in which the normally precise and accurate retinotopic mapping is somehow disturbed in amblyopia. This disturbance leads to both nonveridical perception of location (perceived spatial distortions) and decreased precision of perceived location (elevated vernier thresholds). The second hypothesis proposes a nonuniform anomalous mapping of visual space, analogous to that seen in anomalous retinal correspondence (ARC).1,23,24 This idea is consistent with reports of local targets appearing to be mislocated,25–27 thus suggesting a localized remapping rather than a “scrambling” of the neural map. Finally, Levi and Klein28 and Sharma et al.29 have hypothesized that amblyopes have reduced neural sampling of the foveal map and that this is the root cause of misperception of orientation and poor positional sensitivity.

It is difficult to explain some of the more stable and systematic perceptual errors reported by amblyopes (e.g., large perceived errors in grating orientation18–20,29) with either a neural scrambling model21 or a systematic shift in the neural map.27 Indeed, after quantifying the point-by-point mapping errors observed by amblyopes, Sireteanu et al.17 were unable to predict the perceptual errors that would be seen in grating targets. In addition, preliminary attempts to model neural scrambling by introducing random positional jitter into targets22,30 do not generate the systematic orientation errors seen by some amblyopes. Neural undersampling of high spatial frequencies in normal fovea31 or peripheral retina32 generates spatial aliases that typically have different orientations in relation to the stimulus.29–32 However, in a limited comparison, there are some striking differences between amblyopic perceptions and those seen at high spatial frequencies in normal vision.20,29 Such differences are not surprising, because undersampling in normal vision is a retinal phenomenon,33 whereas the retina of human amblyopes appears normal34 (for a recent review see Hess49). If undersampling is the cause of the per-
ceptual aliases in amblyopes, then it is likely to be cortical in origin, and therefore it should have a different perceptual manifestation.

Although the distorted, scrambled, or aliased perception of gratings is central to both mismapping and undersampling models of human amblyopia, there are few examples of these perceptual errors reported in the literature. The available evidence indicates that visual perception is veridical in at least some amblyopes, but limited sample size makes it difficult to estimate the proportion of amblyopes who experience perceptual errors. The spatial structure of the perceptual errors that have appeared in the literature seems to vary dramatically between individual amblyopes and between studies. Consequently, these discrepancies may reflect a true heterogeneity in the amblyopic population or interstudy differences due to methodology. Nevertheless, it is clear that any neural model of human amblyopia should account for these striking perceptual errors.

In this study, we used the same basic experimental paradigm used originally by Hess et al. to investigate the prevalence of nonveridical visual perception in a large sample of human amblyopes. We wanted to document those perceptual errors that arise when viewing gratings of different spatial frequencies, orientations, and contrasts. The intention was to obtain a rich database of amblyopic misperceptions that could serve to direct future modeling efforts.

**METHODS**

**Stimulus Generation**

Generation and control of stimuli were performed using the macro capabilities of the public domain software NIH Image (version 1.59; developed Wayne Rasband at the National Institutes of Health and available by anonymous FTP from zippy.nimh.nih.gov or on floppy disc from the National Technical Information Service, Springfield, VA). Stimuli were presented on a monitor (MultiSync 15+ Color Display Monitor; NEC, London, UK) with a mean luminance of 41 cd/m² and a frame rate of 66 Hz. The nonlinear luminance response of the display was linearized by using the inverse function of the luminance response, as measured with a photometer (model CS-100; Minolta, Osaka, Japan). Contrast resolution up to 12-bit accuracy was achieved by the video attenuator method. (The host computer was a Power Macintosh 7100/80; Apple Computer, Cupertino, CA.)

The stimuli consisted of circular patches of sinusoidally modulated luminance gratings. Contrast was at its maximum over a central patch 3.2° in diameter. To avoid the presence of sharp edges, the contrast of the grating decreased gradually from maximum to zero with a half-Gaussian profile (σ = 0.615°). The viewing distance was fixed at 2.5 m, and spatial frequency was altered by varying the number of cycles within the patch.

**Recording Amblyopic Misperceptions**

Gratings of various spatial frequencies (1–16 c/deg), orientations (90°, 180°, +45°, and –45°), and contrasts were presented in pseudorandom fashion. Display duration was under the control of the subject. The task of the subject was to view the grating, first with the amblyopic eye and then with the fellow eye. A series of interocular comparisons then took place with the subject holding an occluder and thus controlling the rate at which amblyopic and fellow eye percepts were compared. During this time, the examiner instructed the subject to compare the appearance of the grating in amblyopic and fellow eye viewing and to indicate whether, besides differences in perceived contrast, the percepts differed from one another. Some subjects preferred to exclude light altogether from the nonviewing eye while interocular comparisons were being made, although the method used to occlude the nonviewing eye did not appear to have an effect on the nature or severity of any misperceptions. Subjects were instructed to maintain fixation on the center of the grating throughout. Specific care was taken not to bias subjects and to ensure uniform instructions to every subject. In cases in which the subject indicated that the amblyopic eye viewed the grating differently from the fellow eye, the fellow eye was occluded, and the subject viewed the grating over the same eye. This strategy of viewing stimuli with the amblyopic eye and then rendering them with the nonamblyopic eye parallels the methods used by Hess et al., Sireteanu et al., and Bradley and Freeman, but is different from that used by Sharma et al. who had amblyopes match grating orientation to a line seen with the amblyopic eye.

Sketches were made with a charcoal stick on a large empty circle on white paper. The top of the sheet was clearly marked. Once the sketch had been completed, it was preserved with fixative. To assess repeatability, subjects were asked to repeat some of the sketches that they had made of particular gratings. These repetitions always took place in separate sessions, and subjects were not informed that they were sketching the same grating for a second time or given access to the sketches they had made on the previous occasion. In addition to sketching the appearance of gratings perceived as nonveridical, subjects were also asked to sketch the appearance of a selection of gratings for which the percept was the same for the two eyes. This acted as a form of control, in that sketches of gratings veridically perceived could be compared with the sketches of gratings reported as misperceived. In this way the examiner could assess whether oral reports by the subject of veridical versus nonveridical perception were reflected in the sketches they produced. All drawings of gratings reported herein have been scanned and imaged without manipulation of either the form or content. Rendered images reported are thus accurate representations of the drawings in all ways, with the exception of overall size. These renderings also include the nonlinear distortions of the printing processes, but these are anticipated to have a minor impact on the largely black-and-white original images.

**Amblyopic Subjects**

Thirty amblyopes were assessed (14 with strabismic amblyopia, 10 with anisometropic amblyopia, and 6 with both strabismus and anisometropia). In the context of the present study, amblyopia, in line with Cuhffreda et al., is defined as visual acuity poorer than 20/20 in the absence of any obvious structural or pathologic anomalies, but with one or more of the following conditions occurring before the age of 6 years: amblyogenic anisometropia, constant unilateral exotropia or esotropia, amblyogenic bilateral isometropia, amblyogenic unilateral or bilateral astigmatism, or image degradation. Anisometropia is defined as a difference between corresponding major meridians of the two eyes of at least 1 D. All subjects underwent full refraction and orthoptic assessment before testing. Clinical details are provided in Table 1. Visual acuity was measured with logarithm of minimum angle of resolution (logMAR) charts. All subjects were presented with gratings of various spatial frequencies of at least two orientations (horizontal and vertical). Fifteen subjects (50%) also viewed gratings with oblique orientations (+45° and –45°). The majority (98%) of the drawings made were for gratings of maximum contrast. However, 15 (50%) of the 30 subjects viewed gratings of various spatial frequencies at a range of different contrast levels. In addition to investigation of misperceptions, contrast sensitivity functions were determined for the amblyopic and fellow eyes of each subject, by using a method of adjustment. Each experimental session lasted 1 to 1.5 hours and, depending on the extent to which amblyopic eye misperceptions were reported, up to eight sessions were required for each subject. Although experimentally nonquantitative, our approach of having amblyopic subjects draw a series of gratings provides a rich database of misperceptions against which the outputs from future models of amblyopia can be compared.
TABLE 1. Clinical Details of the Amblyopes

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Diagnosis</th>
<th>Correction</th>
<th>VA</th>
<th>Stabismus</th>
<th>Fixation</th>
<th>Misperception Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK</td>
<td>50</td>
<td>S + A</td>
<td>RE: −0.75/−0.25 × 165</td>
<td>1.58</td>
<td>4 SOT</td>
<td>Nasal sup steady</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LE: +3.50/−1.00 × 70</td>
<td>0.52</td>
<td>4 SOT</td>
<td>Temporal steady</td>
<td>—</td>
</tr>
<tr>
<td>BW</td>
<td>40</td>
<td>S</td>
<td>RE: +1.00/−0.50 × 5</td>
<td>0.12</td>
<td>4 SOT</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>CM</td>
<td>56</td>
<td>S</td>
<td>RE: +4.50/−2.50 × 3</td>
<td>0.52</td>
<td>4 SOT</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>DMc</td>
<td>33</td>
<td>S</td>
<td>RE: −2.50/−1.00 × 175</td>
<td>0.88</td>
<td>8 SOT</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>EF</td>
<td>31</td>
<td>A</td>
<td>RE: −2.00/−0.25 × 150</td>
<td>0.62</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>JM</td>
<td>44</td>
<td>A</td>
<td>RE: +4.50 DS</td>
<td>0.08</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>MM</td>
<td>16</td>
<td>S</td>
<td>RE: +6.50 DS</td>
<td>0.48</td>
<td>8 SOT</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>SL</td>
<td>43</td>
<td>S + A</td>
<td>RE: +0.00/−6.50 × 25</td>
<td>0.32</td>
<td>10 XOT</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>PW</td>
<td>14</td>
<td>A</td>
<td>RE: +0.00/−0.25 × 100</td>
<td>1.20</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>PWa</td>
<td>68</td>
<td>S</td>
<td>RE: +10.00/−2.00 × 110</td>
<td>0.46</td>
<td>—</td>
<td>Nasal steady</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LE: +9.00/−2.50 × 75</td>
<td>0.30</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>CB</td>
<td>42</td>
<td>S + A</td>
<td>RE: +4.50/−0.50 × 160</td>
<td>0.52</td>
<td>4 SOT</td>
<td>—</td>
<td>c, d, e</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LE: +3.00/−0.75 × 85</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>DH</td>
<td>25</td>
<td>A</td>
<td>RE: +0.00/−0.25 × 175</td>
<td>0.60</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>DHi</td>
<td>43</td>
<td>S</td>
<td>RE: −0.25/−1.50 × 110</td>
<td>0.10</td>
<td>10 SOT</td>
<td>Central</td>
<td>c, d</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LE: −0.50/−1.75 × 75</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>DK</td>
<td>65</td>
<td>S + A</td>
<td>RE: +0.25/−0.50 × 95</td>
<td>0.20</td>
<td>5 SOT</td>
<td>Central</td>
<td>b</td>
</tr>
<tr>
<td>DM</td>
<td>62</td>
<td>S</td>
<td>RE: +5.75/−3.00 × 10</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>DM</td>
<td>62</td>
<td>S</td>
<td>RE: +6.75/−2.00 × 165</td>
<td>0.36</td>
<td>8 XOT</td>
<td>Nasal steady</td>
<td>a, e</td>
</tr>
<tr>
<td>DS</td>
<td>30</td>
<td>S</td>
<td>RE: −0.50 DS</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>DW</td>
<td>32</td>
<td>A</td>
<td>RE: +0.50/−0.75 × 175</td>
<td>0.10</td>
<td>—</td>
<td>Central</td>
<td>b</td>
</tr>
<tr>
<td>HF</td>
<td>20</td>
<td>S</td>
<td>RE: +2.75/−1.00 × 125</td>
<td>0.26</td>
<td>10 SOT</td>
<td>Central</td>
<td>a, e</td>
</tr>
<tr>
<td>JS</td>
<td>26</td>
<td>A</td>
<td>RE: +3.50/−0.50 × 100</td>
<td>0.02</td>
<td>—</td>
<td>Central</td>
<td>—</td>
</tr>
<tr>
<td>KR</td>
<td>21</td>
<td>S + A</td>
<td>RE: +1.25 DS</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>b, c</td>
</tr>
<tr>
<td>KS</td>
<td>65</td>
<td>S</td>
<td>RE: +0.25 DS</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>b, c</td>
</tr>
<tr>
<td>LH</td>
<td>46</td>
<td>A</td>
<td>RE: +0.00/−1.00 × 165</td>
<td>1.66</td>
<td>—</td>
<td>Unsteady</td>
<td>e</td>
</tr>
<tr>
<td>MP</td>
<td>27</td>
<td>S</td>
<td>RE: −0.50/−1.00 × 90</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>b, c</td>
</tr>
<tr>
<td>MW</td>
<td>19</td>
<td>A</td>
<td>RE: +4.00/−0.75 × 175</td>
<td>0.58</td>
<td>4 SOT</td>
<td>Nasal</td>
<td>c, d</td>
</tr>
<tr>
<td>MWa</td>
<td>52</td>
<td>S + A</td>
<td>RE: −1.50/−1.00 × 40</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>b, c</td>
</tr>
<tr>
<td>PC</td>
<td>40</td>
<td>S</td>
<td>RE: +0.00/−0.50 × 115</td>
<td>1.20</td>
<td>6 SOT</td>
<td>Nasal sup unsteady</td>
<td>a, b</td>
</tr>
<tr>
<td>RB</td>
<td>28</td>
<td>S</td>
<td>RE: +0.25/−0.25 × 90</td>
<td>0.32</td>
<td>11 SOT</td>
<td>Temporal</td>
<td>b, c, e</td>
</tr>
<tr>
<td>RE</td>
<td>35</td>
<td>A</td>
<td>RE: −3.50/−0.50 × 15</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>b, c</td>
</tr>
<tr>
<td>TM</td>
<td>49</td>
<td>A</td>
<td>RE: −0.50 DS</td>
<td>—</td>
<td>—</td>
<td>Central</td>
<td>b, d</td>
</tr>
</tbody>
</table>

The first 10 subjects have veridical perception, and the remaining twenty show evidence of misperception, as described in the text. Visual acuity is recorded in logMAR notation. S, strabismus; A, anisometropia; SOT, esotropia; XOT, exotropia. Misperception Types: a, wavy; b, abrupt offset; c, misperceived orientation; d, fragmentation; e, scotomatous.
In agreement with Hess et al., our results revealed that the relationship between perceptual errors and anomalies is a major factor in determining the presence of these perceptual errors. It appears that neither etiology nor severity of amblyopia is a completely overlapping visual acuity distributions (Fig. 1). Thus, amblyopes with strabismus and/or anisometropia were found to be nearly equally often in both groups of amblyopes (Fig. 1). Also, visual perception cannot be attributed to differing levels of visual acuity but veridical perception in the amblyopic eye of two subjects with poor visual acuity but veridical perception (BK, PW) and of two subjects with better visual acuity and nonveridical perception (MP, JS). The spatial frequency (in cycles per degree) and orientation (horizontal or vertical) of the gratings are indicated above each sketch.

Informed consent was obtained from all participating subjects after the nature and purpose of the study had been explained, and the research adhered to the tenets of the Declaration of Helsinki.

RESULTS

Proportion of Amblyopes Experiencing Misperceptions

The experimental literature includes examples of amblyopes who experience profound perceptual errors when viewing gratings (e.g., subject TG in Fig. 1 of Hess et al.), whereas perception in other amblyopes is seemingly quite normal. Of the 30 amblyopes examined in the present study, 20 (67%) reported perceptual anomalies. The prevalence of distorted visual perception cannot be attributed to differing levels of amblyopia, because the two groups have completely overlapping visual acuity distributions (Fig. 1). Also, amblyopes with strabismus and/or anisometropia were found about equally often in both groups of amblyopes (Fig. 1). Thus, it appears that neither etiology nor severity of amblyopia is a major factor in determining the presence of these perceptual anomalies.

Relationship between Perceptual Errors and Contrast Sensitivity

In agreement with Hess et al., our results revealed that the incidence and severity of anomalous visual perception in amblyopes viewing with the affected eye was not linked to the presence of a contrast-sensitivity deficit. Figure 2 shows examples of mild contrast-sensitivity losses in subjects with marked misperceptions, whereas our complete data set includes several examples of veridical perception in cases of marked contrast-sensitivity loss (not shown).

Effect of Spatial Frequency

In common with several previous investigations, we found a strong correlation between the prevalence and severity of perceptual distortions and the spatial frequency of the viewed grating. Our database of sketches contains many examples of veridical perception at low spatial frequencies but with perceptual distortions becoming increasingly manifest at higher frequencies. Examples of the spatial-frequency selectivity of this phenomenon are shown in Figure 2. Perception seemed universally normal at 1.25 cyc/deg, but perceptual distortions increased in frequency and severity with increasing spatial frequency. It is important to stress that these spatial distortions can occur at spatial frequencies far below the detection acuity cutoff.

Categorizing the Perceived Distortions

From our sample of 20 sets of drawings of anomalous perceptions, it is possible to divide them into generally distinct classes of distortion. It is not clear whether such a post hoc classification has any functional significance, and it is included merely as a way to make general statements about a very complex data set. For this purpose, the data have been grouped into five categories. It is important to note that the same amblyope can be classified into different categories when viewing different spatial frequencies and orientations. Examples of each class of perceptual distortion are shown in Figure 3, and Table 1 provides details of the types of misperceptions experienced by each subject.

Figure 3a shows five examples of a “wavy”, or positionally modulated, appearance of straight gratings. These are strikingly similar to those drawn by subject JK in Sireteanu et al. Sometimes the waves are quite low in frequency (e.g., subject MWa), whereas in other cases, they seem to be very high in frequency (e.g., subject MK). These drawings are a representation of what subjects saw when looking at the center of the grating. Four (20%) of the 20 subjects in the nonveridical group showed evidence of this type of misperception.

Figure 3b shows five examples of a “jagged” type of perceived positional modulation also reported previously (Hess et al., subjects TG and PS). In these examples, the gratings appear to have multiple, abrupt positional shifts orthogonal to the gratings orientation. Again, these sometimes have a large spatial scale (e.g., subject MWa), and in others they have very high repetition rates (e.g., subject KR). Twelve (60%) of the 20 amblyopes with anomalous perception reported such distortions (e.g., subject MWa), whereas in other cases, they seem to be very high in frequency (e.g., subject MK). These drawings are a representation of what subjects saw when looking at the center of the grating. Four (20%) of the 20 subjects in the nonveridical group showed evidence of this type of misperception.

The third category of perceptual distortion is shown in Figure 3c. These subjects reported errors in perceived orientation. These errors were observed by 11 (55%) of the 20 amblyopes in whom nonveridical perception was revealed, and they came in two general varieties. In some cases, the correct grating orientation is seen with an additional, often lower-contrast, grating superimposed at some oblique orientation. Examples include sketches made by subjects MW and JS in which the spuriously oriented patterns formed angles of approximately 50° and 30° respectively, with the true stimulus orientation. A second and more common percept was of two orientations, often symmetrically rotated on either side of the true stimulus orientation. Figure 3c also shows examples of this type of misperception (e.g., subjects MP, RB). In some cases, the spururious orientations differed markedly from the true grating orientation (e.g., subject MP), whereas in others the twin erroneous gratings are closely matched in orientation to the true orientation. To summarize, some subjects saw only erroneous orientations, whereas others saw the veridical orientation and nonveridical orientations. The cases in which two orientations are perceived, neither of which reflects the true
stimulus orientation, are reminiscent of the bimodal pattern of orientation-matching errors evident in some of the data described by Sharma et al. Spurious orientations are also evident in the sketches made by amblyopic subjects in several previous investigations (Hess et al., subject NN; also Refs. 19, 20).

The fourth class of perceptual error contains fragmented drawings in which the gratings appeared to be broken or have gaps (Fig. 3d). Six (30%) of the 20 subjects in the nonveridical group showed evidence of this type of misperception. Perceptual anomalies of this kind are also evident in the sketches made by subjects PS and RT in Hess et al.

The fifth group of drawings (Fig. 3e) includes all those with large gaps in the grating, as distinct from gaps in individual lines within the grating (Fig. 3d). These gaps in perception were analogous to classic scotomas and in some cases were well centered on the grating patch, but often were asymmetric or quite irregular in shape. The most striking examples of this irregularity are the scotomas drawn by subject PC (Fig. 2 contains additional examples of this misperception by the

**Figure 2.** Seven examples showing the increased tendency for subjects to misperceive gratings of higher spatial frequency. The spatial frequency (in cycles per degree) and orientation (horizontal or vertical) of the test grating are shown above each corresponding sketch. Rightmost column: contrast sensitivity functions for the amblyopic (open symbols) and fellow (filled symbols) eyes. The ticks on the abscissa of the contrast sensitivity plots correspond to spatial frequencies of 1 and 10 cycles per degree. The ticks on the ordinate correspond to contrast sensitivities of 1, 10, and 100. Each row of sketches was made by a single subject.
same subject). In total, 7 (35%) of the 20 subjects in the nonveridical group showed evidence of this type of misperception. This type of percept was also reported by Hess et al.18 (subjects ST, AC, and NN) and Sireteanu et al.17 (subject JK).

Because the drawings often contained more than one phenomenon, the groupings we used to describe the data are not exclusive. One example of this was in subject RB (Fig. 3). The most striking feature of this subject’s drawing was the large scotoma (hence it is included in Fig. 3e), but outside the scotoma, the perception clearly included anomalous orientations. Table 1 reveals that most of the subjects in the nonveridical group showed evidence of more than one type of misperception. Examination of the sketches that appear in Hess et al.18 also reveals several subjects whose misperceptions cannot be classified into a single distortion category (e.g., subjects PS, NN, and PT).

**Effect of Orientation**

The striking orientation component of the perceptual errors (Fig. 3c) raises the obvious question of how these perceptual distortions vary with grating orientation. Figure 4 shows data from seven subjects, all of whom made drawings while viewing vertical and horizontal gratings. In the case of one subject, drawings were also made of obliquely oriented gratings (row 1, subject MK). In each case, the perceptual distortions varied with grating orientation. For example, spurious orientations might be seen with vertical gratings, but some other distortion with horizontal gratings (and vice versa), and in some cases, perception seemed veridical at one orientation and distorted at another. Our results reveal that of the 15 subjects in the nonveridical group who viewed gratings at all four orientations, 11 (~73%) showed evidence of an orientation-dependent effect, whereas only 4 (~27%) reported a distortion that was invariant with grating orientation. Of the 11 subjects in whom perceptual errors showed an orientation dependency, three subjects exhibited veridical perception for horizontal orientations, whereas distortions were evident at oblique and vertical orientations in all 11 subjects.

**Effect of Contrast**

All previous studies of suprathreshold grating perception in human amblyopes have used a single contrast for all gratings. Similarly, all sketches of gratings shown in Figures 1 to 4 were of stimuli with maximum contrast. We wondered whether the perceptual distortions present at high contrast would also be evident at lower contrast levels. Drawings of the same grating orientation and spatial frequency but different contrasts are shown in Figure 5. Two patterns were observed. For two subjects (Fig. 5, top row) the same basic pattern of distortions was exhibited at both low and high contrasts. That is, the waves (subject HF) and scotomas (subject KS) were generally unaffected by these contrast changes. For the other two subjects (RB and DK), the perceptual errors recorded with high-contrast gratings disappeared at low contrasts. In both of these subjects, the low-contrast gratings appeared almost veridical, in spite of highly salient distortions at high contrast. Overall, of the 15 subjects in the nonveridical group who viewed gratings at a range of different contrast levels, 7 (~47%) experienced misperceptions that became less pronounced as contrast was reduced.

**Repeatability of Drawings**

In requiring artistically untrained subjects to draw their complex perceptions, we anticipated errors due either to poor
drawing skills or to an inability of such a drawing to render accurately what subjects perceived. We therefore adopted two approaches to assess validity and reliability of the drawings. First, to ascertain that these clearly nonveridical drawings were unique to amblyopia and specific to those amblyopes who report distorted perceptions, we asked normal subjects and amblyopes who reported normal perception to draw gratings. Normality of the amblyopic perception was examined by having these amblyopes draw gratings as they appeared to both their amblyopic eyes (AE) and their fellow nonamblyopic eyes (FE). Although these drawings (not shown) were not veridical in a precise fashion, no distortions of the types shown in Figures 2 to 4 were evident, and the AE and FE drawings were very similar to one another and to the drawings made of the same stimuli by subjects without amblyopia. This confirms that the nonveridical drawings shown in Figures 2 to 4 were unique to those amblyopes who reported distorted perception.

However, it is not possible to ascertain the accuracy of these drawings by this method. One indirect approach to assessing the accuracy is to examine repeatability. The idea is that if a patient always draws the same distortion, then it is a representation of a stable perceptual phenomenon and presumably reflects some recognizable structure in the perceived grating. Repeatability is easily assessed by simply repeating the experiment at a later time. After the initial experimental session(s), 10 (50%) of the 20 subjects with anomalous perception returned to the laboratory and were asked to make sketches of gratings that they had sketched during an earlier visit to the laboratory. Subjects were not informed that they were repeating the same conditions. Figure 6 shows 12 examples of such repetitions. Considering the complexity of the task, the repeatability of our approach is striking and adds considerably to the impression that these perceptual errors are both highly salient and generally stable over time. However, many of our am-

---

**Figure 4.** Examples of sketches from seven subjects in whom the type or existence of the distorted perception changed for gratings of different orientation. The spatial frequency (in cycles per degree) and orientation (horizontal or vertical) of the test grating are shown above each corresponding sketch. With the exception of subject **MK** (top row), the sketches are grouped into pairs of the same spatial frequency and perpendicular orientations. For subject **MK** at 8 cyc/deg, sketches are also shown for orientations of 30° and 145° counterclockwise from horizontal.
blyopes reported that their distortions were temporally unstable on a short time scale (e.g., subject MP).

The control and repeated-measures data both suggest that our subjects’ drawings were reasonably accurate renditions of highly salient perceptual errors not present in normal-vision subjects or approximately one third of amblyopes.

DISCUSSION

Prevalence of Misperceptions in Amblyopia

Previous studies of perceptual distortions of grating stimuli in amblyopia have been limited by small samples of subjects, making the prevalence of perceptual distortions among amblyopes difficult to quantify. For example, Hess et al.\(^\text{18}\) stated that grating stimuli were misperceived by ‘most’ amblyopes (it appears that at least three of eight subjects had anisometropic amblyopia\(^\text{21}\)). Bradley and Freeman\(^\text{19}\) found nonveridical perception of gratings in four of six amblyopes (one anisometrope, one esotrope, and two anisometropic exotropes). Thibos and Bradley\(^\text{20}\) reported distorted perception of gratings in one subject with strabismic amblyopia, Sharma et al.\(^\text{29}\) in two of three with strabismic amblyopia, and Sireteanu et al.\(^\text{17}\) in at least one with strabismic amblyopia. Salient misperceptions were reported by 20 of 30 amblyopes in our study (64% of those with strabismus, 70% of those with anisometropia, and 66% of those with mixed amblyopia). Prevalence of spatial misperceptions may be even higher than our data indicate if some distortions are not recorded in the drawings or the subjective reports.

![Figure 5](image1.png)

**FIGURE 5.** The effect of contrast on the incidence and severity of misperceptions. The suprathreshold contrast level is indicated as a multiple of the detection threshold for the subject viewing that particular grating stimulus. The spatial frequency and orientation of the test grating are also indicated. Each group of sketches is from a single spatial frequency presented at decreasing levels of contrast. The subjects in the upper row (HF, KS) reported that the perception remained the same as the contrast decreased until the grating was no longer visible. The subjects in the lower rows (RB, DK) reported that the gratings became less distorted as the contrast decreased. In the case of subject KS, the viewing distance was 1.25 m, thus explaining the increased number of cycles drawn.

![Figure 6](image2.png)

**FIGURE 6.** The repeatability of the methodology used was confirmed by having subjects draw misperceived gratings on two separate occasions. Each pair of sketches represents the same spatial-frequency grating drawn by the same amblyope. Subjects were not aware that they were sketching a grating they had sketched before, nor were they given access to any previous sketches they had made. The orientation and spatial frequency of the test grating are indicated above the pairs of sketches.
Several investigations have revealed that persons with strabismic amblyopia exhibit large constant errors in spatial alignment and partitioning tasks. However, these distortions of spatial geometry were not found in those with anisotropic amblyopia. It appears therefore, that there may be two forms of perceptual distortion in human amblyopia: One is restricted to strabismic amblyopia, which is analogous to a large-scale but nonuniform change in the retinotopic map somewhat similar to ARC, a condition found exclusively in strabismus. The second, found equally often in most persons with anisometropia or strabismus, produces anomalous perceptions of grating stimuli.

**Structure of Perceptual Errors**

The universal feature of our data and the previous reports is the obvious spatial-frequency dependency of this effect. Misperceptions were absent at the very lowest spatial frequencies but become increasingly obvious with increasing spatial frequency. In previous studies within our single study suggests that the spatial frequencies and orientations tested.

3), however, reported the same type of perceptual error at all stimulus orientations at 3 cyc/deg (Fig. 3). Also, the type of perceptual error for some subjects clearly changed with stimulus orientation. For example, subject CB reported vernier-like offsets for vertically oriented gratings at 5 cyc/deg (Fig. 3) but anomalous lines (see also Sireteanu et al.). Bradley and Freeman and Thibos and Bradley reported drawings of anomalous grating orientations made by amblyopes, but no vernier-like offsets or wiggles were apparent in the lines. Orientation errors were also evident in sketches made by one subject in Hess et al., and, in a recent investigation, Sharma et al. quantified orientation misperceptions in a matching study. Furthermore, Hess et al. reported spatial-frequency-specific scotomas in some subjects. That is, gratings appeared to be absent in local, mostly central, areas of the display, but only with higher-frequency stimuli. Finally, Hess et al. also reported amblyopes who saw fragmented individual stripes in the gratings.

Observing all the different reported distortions described in previous studies within our single study suggests that the previous between-study differences may have reflected qualitatively distinct phenomena. First, grating lines exhibited positional errors that were either abrupt offsets or wiggles in the lines (see also Sireteanu et al.). Bradley and Freeman and Thibos and Bradley reported drawings of anomalous grating orientations made by amblyopes, but no vernier-like offsets or wiggles were apparent in the lines. Orientation errors were also evident in sketches made by one subject in Hess et al., and, in a recent investigation, Sharma et al. quantified orientation misperceptions in a matching study. Furthermore, Hess et al. reported spatial-frequency-specific scotomas in some subjects. That is, gratings appeared to be absent in local, mostly central, areas of the display, but only with higher-frequency stimuli. Finally, Hess et al. also reported amblyopes who saw fragmented individual stripes in the gratings.

Implications for Models of Amblyopia

The high prevalence, salience, and repeatability of these perceptual distortions indicate that they reflect a significant neurologic anomaly in many human amblyopes. Below, we consider the implications of these data for the two general neurologic models described in the literature and we introduce an alternative cortically based model of human amblyopia.

Uncalibrated Topographical Disarray. The original observation by Hess et al. of perceptual distortions led them to reject a low-pass filtering model of amblyopia and they used the term tarachopia (scrambled vision) as a substitute for the classic term amblyopia (blunt vision) to distinguish it from simple low-pass filtering. This positional error model has been described by others as neural scrambling or jumbling, uncalibrated distortions, uncalibrated disarray, and intrinsic spatial disorder.

Although topographical disarray is a neural hypothesis to explain the positional displacements seen by some of the subjects in Hess et al., it cannot easily account for some of the systematic perceptual errors experienced by some amblyopes. In particular, the perceived errors in orientation (Refs. 18-
Hess et al. 22 simulated two types of positional disarray: simple retinotopic positional jitter and random-phase shifting of a Gabor-filtered image. Phase-shifting produced perceptual distortions quite different from simple topographical disarray, but neither type of jitter can create errors in perceived orientation of gratings such as those reported by amblyopes.

The evidence in support of topographical disorder in amblyopia comes mainly from equivalent noise studies.10,23 The approach involves determination of the level of external positional noise (jitter) that raises psychophysical position (e.g., vernier) thresholds by a criterion amount. The results reveal that amblyopic vision is more resistant to positional disorder of the stimulus than is normal vision. This is presumed to reflect increased equivalent positional noise within the visual system, which, in turn, is interpreted as evidence in support of the topographical disorder hypothesis of amblyopia. However, these data are difficult to interpret because the effect of stimulus jitter is spatial-scale dependent.25 Although the spatial scale of the stimulus may be fixed, subjects are capable of choosing the most useful scale within the stimulus to perform positional alignment tasks.44 For example, as the gap between the elements of a vernier stimulus is increased, alignment is determined by progressively coarser spatial scales (i.e., lower spatial frequencies) within the stimulus.44–46 For this reason, the introduction of spatial disorder has less effect on positional acuity with larger gaps.47 Amblyopes tend to use larger spatial scales on visual tasks than normal-vision subjects.48 Therefore, it is possible that the increased tolerance to stimulus jitter observed in amblyopes40,42 may reflect the fact that, on some tasks, amblyopes use a larger spatial scale and not that they have increased internal disarray.41

Retinotopic Undersampling. Retinotopic undersampling has been used to explain visual misperceptions in response to spatial frequencies above the retinal sampling limit.43–52 Could it also apply to a cortical deficit such as amblyopia? Levi and Klein50 originally proposed undersampling to explain the enlarged distance over which additional samples of a line represented vernier acuity in subjects with strabismic amblyopia. However, as with the equivalent noise experiments just described, their results may reflect the fact that amblyopes use lower-than-normal spatial frequencies (larger spatial scales) to perform the task. Additional experiments using sampled stimuli have been interpreted as evidence that amblyopic vision undersamples the retinal image.10,11,28,45,49–52 However, experimental studies in which more traditional grating stimuli were used to examine neural sampling31,53 failed to find any evidence of retinotopic undersampling in human amblyopia. Sharma et al.29 used an experimental method developed to look for orientation reversals for spatial frequencies at twice the Nyquist limit.52 Contrary to predictions, two of three subjects with strabismic amblyopia reported striking errors in perceived orientation at spatial frequencies far below the resolution limit, and, in a third subject, perceived orientation was quite normal at all spatial frequencies. Also, the two other primary predictions of a simple retinotopic undersampling model (motion reversals54 and systematic misperception of frequency18–26) have not been observed. From a neurophysiological standpoint, the dramatic remapping of the neural image at the cortex from a simple (albeit distorted) point by point sampling to a multifaceture polymap55 makes it unlikely that retinotopic-based undersampling explains amblyopic misperceptions.

A Cortical Model of Amblyopic Misperceptions. In addition to the large body of experimental literature indicating that amblyopia in animals is a cortical phenomenon, human ERG studies (see review in Ref. 35) and recent functional magnetic resonance imaging (fMRI) data56 indicate that the deficit in human amblyopia is not in the retina or lateral geniculate nucleus (LGN) but in the primary visual cortex (although possibly not in the input layers57–59). This body of work suggests that a model of neural undersampling of the retinal image is unlikely to account for amblyopic vision. Instead, the data suggest that a model of neural undersampling in amblyopia should be formulated in the orientation and spatial-frequency domains native to the primary visual cortex.60–62 Such a model would seek to account for systematic errors in perceived orientation reported by amblyopes and, at the same time, acknowledge that the appearance of gratings to many amblyopes cannot be explained by classic undersampling or positional noise in the retinotopic domain.

A key observation that motivated the model about to be described is that many amblyopes who reported spurious perceptions actually drew two orientations with the nonamblyopic eye. This suggests that an individual with normal vision can gain insight into the nature of amblyopic perception of single gratings by viewing pairs of superimposed gratings of different orientations. Several examples are illustrated in Figure 8. This idea of simulating amblyopic vision by distorting the neural representation of stimulus orientation in the amblyopic eye is similar to the cortical neural image of two obliquely oriented gratings viewed by the nonamblyopic eye. This suggests that an individual with normal vision can gain insight into the nature of amblyopic perception of single gratings by viewing pairs of superimposed gratings of different orientations. Thus, it is not necessary to postulate neural mechanisms that scramble the retinotopic mapping of the cortical neural images (Hess et al.18), because positional distortions may in fact be manifestations of errors in the orientation code. In discussion that follows, we examine our neural model in the context of current neuroanatomical and neurophysiological understanding of amblyopia.

The simulations in Figure 8 reveal the numerous perceptual ramifications of a neural system that misrepresents a single orientation as two different orientations. In addition to the generation of the expected dual grating appearance, we are struck by the ability of these simulations to generate all the perceptual errors (wiggly lines, abrupt offsets, areas of low contrast, and segmented lines) observed by our amblyopes and those in previous studies.

The successful simulation in Figure 8 of most of the features of amblyopic vision observed in our study suggests that amblyopic misperception of gratings could be accounted for if the neural representation of stimulus orientation in the amblyopic visual cortex misrepresents a single orientation as a pair of orientations. Thus, it is not necessary to postulate neural mechanisms that scramble the retinotopic mapping of the cortical neural images (Hess et al.18), because positional distortions may in fact be manifestations of errors in the orientation code. In discussion that follows, we examine our neural model in the context of current neuroanatomical and neurophysiological understanding of amblyopia.

The functional mapping of area V1 of normal visual cortex has shown that ocular dominance, orientation, and spatial frequency are all topographically mapped across the cortex. Oc all spatial frequency is mapped as bands running orthogonal to the surface and traversing all layers of V1.63–65 Orientation is represented in radial patterns, sometimes twisted into a pinwheel appearance.61,62 Although the details of spatial-frequency mapping remain somewhat controversial, it appears that in the macaque the high and low frequencies are mapped into different areas of the ocular-dominance columns.66 One striking feature of these various maps is that they are not
independent of each other. For example, there is evidence that orientation maps and spatial-frequency maps are both correlated with the ocular-dominance maps.\textsuperscript{60,63,65} That is, low-spatial-frequency cells cluster around the cytochrome oxidase "blobs" located at the center of the ocular-dominance columns,\textsuperscript{60} whereas high-spatial-frequency, orientation-selective cells cluster around the boundaries between left and right eye ocular-dominance columns.\textsuperscript{66} Discontinuities in the orientation map generally cluster around the more monocular regions of V1.\textsuperscript{66}

Ocular-dominance maps in the visual cortex of animals rendered amblyopic through monocular deprivation of normal vision during development are abnormally narrow for the deprived eye and abnormally wide for the fellow eye.\textsuperscript{64,67,68} This expansion of the neural territory dominated by one eye at the expense of the other eye occurs first at the boundary between ocular-dominance columns, which is also the location of the high-frequency component of the spatial-frequency map. Consequently, this reorganization of the ocular-dominance map associated with amblyopia should selectively affect vision of higher spatial frequencies. Consistent with this expectation, monkeys atropinized during early development exhibit visual loss of contrast sensitivity at high spatial frequencies,\textsuperscript{69} reduced deoxyglucose labeling in V1 when the amblyopic eye was stimulated with medium (but not low) spatial frequencies,\textsuperscript{70} reduced spatial resolution of individual cells responding to the atropinized eye,\textsuperscript{71} and an overall shift in ocular dominance toward the nonamblyopic nonatropinized eye.\textsuperscript{71} Similarly, the perceptual errors reported in our study (Fig. 2) and the contrast sensitivity deficits reported by others typically become more pronounced at higher spatial frequencies.

**FIGURE 8.** Examples showing how two component gratings (two left columns), when summed (column three), can generate spatial patterns qualitatively very similar in appearance to the varied misperceptions that arise in amblyopia (rightmost column) when viewing a single grating. The orientation of the grating stimulus and number of cycles presented on the screen is indicated beside the amblyopic percept (rightmost column). In most of these examples, the two component gratings differ in orientation, but not in spatial frequency (rows 1 and 5 also contain spatial frequency differences). Also, in every case except rows 1 and 7, the two component gratings have identical contrasts.
Furthermore, because orientation is mapped in radial patterns centered on ocular-dominance columns, orientations represented by cells located on the border between ocular-dominance columns are more at risk of becoming dominated by the nonamblyopic eye. However, cells representing orientations rotated $\pm 45^\circ$ from those at the ocular-dominance border are located near the ocular-dominance column's center. Thus, shrinkage of ocular-dominance columns should always produce an effect that varies with orientation, which agrees well with the perceptual distortions we observed in amblyopes.

A single grating stimulus would be expected to excite a population of neurons to varying degree because of the finite orientation bandwidth of cortical neurons.\textsuperscript{72,73} Normally, the strength of this neural response to a single grating would be a unimodal function of orientation, but it is conceivable that the distribution could become bimodal in the amblyopic ocular-dominance column if neurons in the center of the distribution are lost to the fellow eye. The result would be an amblyopic neural image similar in form to the bimodal neural image created in normal visual cortex by a pair of gratings of different orientation. Thus the amblyope would report that a pair of gratings viewed with the normal eye has an appearance similar to that of a single grating viewed with the amblyopic eye, because both stimuli produce bimodal distributions of neural activity in the visual cortex.

A small number of studies have addressed the question of whether the normal ocular-dominance column arrangement in humans is affected by amblyopia.\textsuperscript{57,58} No shrinkage of amblyopic eye representation was found at autopsy in layer IVc in a human amblyopic eye ocular-dominance columns for two reasons. First, it is likely that ocular-dominance patterns in layer IVc are lost to the fellow eye. The result would be an amblyopic neural image similar in form to the bimodal neural image created in normal visual cortex by a pair of gratings of different orientation. Thus the amblyope would report that a pair of gratings viewed with the normal eye has an appearance similar to that of a single grating viewed with the amblyopic eye, because both stimuli produce bimodal distributions of neural activity in the visual cortex.

Although our model remains somewhat speculative at present, we conclude that the misperception of grating stimuli reported by amblyopes may be a direct consequence of the reduced neural representation of the amblyopic eye signal in the primary visual cortex.

Acknowledgments

The authors thank David Whitaker for software support.

References

32. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.
34. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.
35. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.
41. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.
42. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.
43. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.
44. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.
46. Hess RF, Field DJ. Is the spatial deficit in strabismic amblyopia due to loss of cells or uncalibrated disarray of cells. Vision Res. 1994;34:5397–5406.