

Deficits in Perception of Images of Real-World Scenes in Patients With a History of Amblyopia

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Objectives: To investigate the perception of images of real-world scenes in patients with amblyopia and to compare their performance with that of visually normal participants by viewing conditions (monocular vs binocular) and by treatment outcomes (successfully vs unsuccessfully treated vs normal eyes).

Methods: Thirty-nine healthy and 26 amblyopic individuals who had undergone previous amblyopia treatment were recruited to perform a match-to-sample task that used images of real-world scenes. Rates of correct, incorrect, and no responses and mean reaction time were recorded.

Results: Performance during monocular viewing showed that the mean correct response rate was 59% in the amblyopic eyes, 62% in the fellow eyes, and 67% in the normal eyes ($P=.008$). During binocular viewing, the cor-

rect response rate remained reduced at 58% in amblyopic patients compared with 68% in participants with normal vision ($P=.03$). Performance by treatment outcomes showed that the mean correct response rate was 59% in the unsuccessfully treated group, 64% in the successfully treated group, and 67% in the normal group ($P=.002$). There was no difference in performance among amblyopia subtypes.

Conclusions: Real-world scene perception is impaired in amblyopia, with the poorest performance during amblyopic monocular and binocular viewing. Despite successful treatment of the amblyopic eye to normal acuity levels, perception of images in real-world scenes remains deficient in patients with a history of amblyopia.

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AMBLYOPIA IS A VISUAL impairment of 1 or both eyes caused by inadequate use during early childhood that cannot be corrected immediately by optical means.¹ It is estimated to affect 3% to 5% of people in the Western world and is the primary cause of monocular blindness.²⁻⁸ Amblyopia is associated most commonly with early childhood strabismus (eye misalignment), anisometropia (difference in refractive errors between the 2 eyes), or both (ie, mixed mechanisms). In addition to deficits in visual acuity and contrast sensitivity,⁹⁻¹¹ amblyopic patients show abnormal higher-level perception, including deficits in global form and motion integration,¹²⁻¹⁶ global contour processing,¹⁶⁻¹⁸ second-order motion detection,¹⁹⁻²¹ Vernier acuity/positional uncertainty,¹¹ symmetry detection,²² and other types of complex motion detection.²³ Deficits on tasks that involve higher-order attentional components, including underestimation in a visual object enumeration task,²⁴ prolonged attentional blink,²⁵ and decreased accuracy when tracking single or multiple objects,²⁶ are also evident in amblyopic patients. In addition, the fellow eye in amblyopic patients demon-

strates smaller deficits in contrast sensitivity,²⁷ Vernier acuity/positional uncertainty,²⁸⁻³⁰ contour detection or detection of second-order image characteristics,^{19,31,32} and detection of motion-defined form^{33,34} exist concurrently with deficits in the amblyopic eye.

In previous studies⁹⁻³⁴ of visual deficits in amblyopia, the investigators have focused on specific aspects of vision and performed experiments to test the variables relevant to their hypotheses. However, a major question that remains unexplored is whether amblyopia affects the perception of objects and scenes during everyday activities. In the present study, we showed amblyopic patients a sample image consisting of an everyday scene or object and asked them to match it to an identical image among a group of similar "distractor" images. Our first goal was to assess how well amblyopic patients identified and matched images of real-world scenes and to compare their performance with that of participants with normal visual acuity (hereinafter referred to as visually normal participants) during different viewing conditions, namely, monocular viewing (amblyopic vs fellow vs normal eyes) and binocular viewing (amblyopic patients vs visually normal participants).

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In this report, *fellow eye* refers to the nonamblyopic eye of amblyopic patients, and *normal eye* refers to eyes of visually normal participants.

A second goal of this study was to determine whether successful treatment of the amblyopic eye by clinical criteria had any influence on the perception of images of real-world scenes. Many previous studies^{11,16,26,28,31,35-37} have examined the visual deficits in amblyopia by combining patients with and without previous treatment. Those studies did not investigate specifically whether other visual deficits remained after successful treatment by acuity criteria (ie, after visual acuity improves to normal) or whether the severity of these deficits differed between successfully and unsuccessfully treated eyes. In this study, we investigated whether the perception of images of real-world scenes differs between successfully treated eyes and normal eyes with the same acuity level (20/25 or better) and between successfully and unsuccessfully treated eyes that underwent previous amblyopia treatment.

METHODS

PARTICIPANTS

Twenty-six amblyopic patients and 39 visually normal individuals aged 9 to 65 years were recruited from a private practice of one of us (S.H.). For the purpose of this study, *amblyopia* was defined as a visual acuity of 20/40 or worse in the amblyopic eye and an interocular difference of 2 or more chart lines at diagnosis. *Strabismic amblyopia* was defined as amblyopia in the presence of eye misalignment at distance, near fixation, or both. *Refractive/anisometropic amblyopia* was defined as amblyopia in the presence of a difference in refractive error between the 2 eyes of 0.50 diopters (D) or more of spherical equivalent or a difference in astigmatism in any meridian of 1.50 D or more. *Mixed-mechanism amblyopia* was defined as amblyopia in the presence of a combination of strabismus and anisometropia. People with any ocular cause of reduced visual acuity, high myopia (-6.00 D or more), or prior intraocular surgery were excluded from the study. All amblyopic patients had undergone previous treatment (eg, glasses, monocular occlusion, penalization, strabismus surgery, or any combination of these treatments). Best-corrected visual acuity was recorded at diagnosis and at the time of the experiment. *Treatment success* was defined as achieving a visual acuity of 20/25 or better in the amblyopic eye or an interocular difference of 1 line or less. Visually normal participants had a visual acuity of 20/25 or better in both eyes and normal binocular vision (≤ 40 arc seconds). The research protocol adhered to the tenets of the Declaration of Helsinki. Informed consent was obtained from all participants.

IMAGE SELECTION

Images were chosen from a database of more than 1400 images taken by the experimenters. Although images used within a particular trial were highly similar (in their perspective or in the similarity of the objects), across trials the images were diverse and nonspecific. These pictures were made up of everyday scenes indoors or outdoors and of varying textures or objects and were taken from relatively near or far distances.

Of the total database of images, a subset of 320 was chosen for a match-to-sample task (a sample of these images is shown in **Figure 1**). This subset was chosen on the basis of image quality and similarity. Effort was also made to include as diverse a range of images as possible in this subset to reflect a

realistic range of perspectives an individual living in North America might encounter.

PROCEDURE

All participants performed a match-to-sample task. For those with amblyopia, affected and fellow eyes were tested separately in a random order. Those in the control group had 1 randomly chosen eye tested for comparison. Participants were seated 70 cm in front of a computer monitor. Eighty trials were randomly shown during the task. Each trial consisted of a reference image shown on the right side of the screen subtending a visual angle of 8°. Simultaneously, on the left side of the screen, 4 choices were displayed in a 2×2 array, each within a circular aperture that was 5° in diameter (**Figure 2**). One of these 4 choices was identical to the reference image, whereas the other 3 choices resembled the reference image but were not identical to it. That is, the incorrect choices were of the same object or scene but taken from a different perspective or were of a similar but not identical object. Overall, the correct response rate of all participants ranged from 31% to 90%; thus, the difficulty level of the 80 trials varied considerably, with some individual trials consistently being easier and others more difficult to complete.

Each trial was shown for 5 seconds, during which the reference image and the 2×2 array were viewed freely. Participants used a mouse-click to select the choice that they thought matched the reference image. If they did not respond within the 5-second period, the trial ended and was scored as no response, and the following trial began immediately.

DATA ANALYSIS

The rates of correct, incorrect, and no responses were calculated in percentages from the 80 trials for each participant. The mean reaction time for each correct response was also recorded. These 4 performance measures were compared among the 3 monocular viewing conditions (amblyopic eye, fellow eye, and normal eye) and the 2 binocular viewing conditions (amblyopic patients and visually normal participants) using analyses of variance (ANOVAs). These 4 performance measures were also compared among treatment outcomes of the amblyopic eyes (failure and success) and the normal eyes and among amblyopia subtypes (strabismic, refractive/anisometropic, and mixed-mechanism) by means of ANOVAs.

To assess whether performances systematically worsen from the normal eye to the fellow eye to the amblyopic eye, contrast analyses were conducted for all significant ANOVAs. To examine whether the differences in performances among the amblyopic, fellow, and normal eyes were due to differences in visual acuity, correlation coefficients were calculated between mean correct response rate and best-corrected visual acuity. Unless otherwise indicated, data are expressed as mean (SD).

RESULTS

The mean age was 38.0 (20.6) (range, 9-64) years for the amblyopic patients and 37.1 (17.9) (range, 10-64) years for visually normal participants (unpaired, 2-tailed *t* test, $P = .85$). Ten of the 26 amblyopic patients (39%) had strabismic amblyopia, 13 (50%) had refractive/anisometropic amblyopia, and 3 (12%) had mixed-mechanism amblyopia. At the time of the experiment, best-corrected visual acuity in the treated amblyopic eye was 20/25 or better in 8 (31%), 20/30 to 20/40 in 12 (46%), 20/50 to 20/80 in 4 (15%), and 20/100 to 20/200 in 2 (8%)

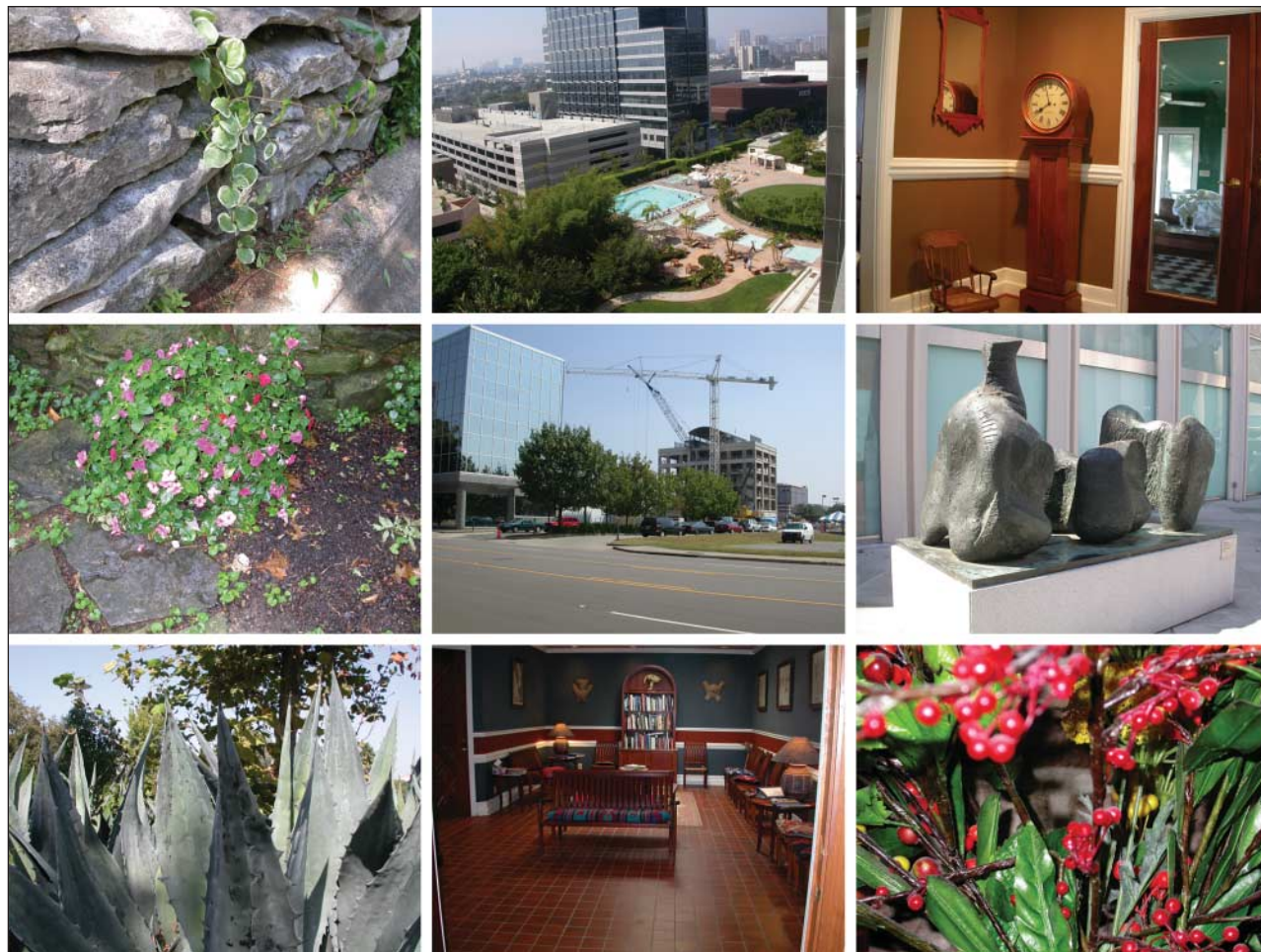


Figure 1. A sample of images used in the match-to-sample task.

of the amblyopic patients. Thus, 8 of 26 amblyopic patients (31%) had successful treatment (ie, 20/25 or better), whereas 18 (69%) had failed treatment (ie, 20/30 or worse).

PERFORMANCE BY VIEWING CONDITIONS

Monocular Viewing

The mean correct, incorrect, and no response rates for the 3 monocular viewing conditions are shown in **Figure 3**. A significant difference in correct response rates was found among the 3 monocular viewing conditions, including 59% (9%) during amblyopic eye viewing, 62% (9%) during fellow eye viewing, and 67% (10%) during normal eye viewing ($F_{2,24}=5.88$; $P=.008$). There was a significant increase in the correct response rates from amblyopic eye to fellow eye to normal eye ($F_{1,24}=10.73$; $P=.003$). The difference in correct response rates was not due to a difference in visual acuity; the correlation coefficient between correct response rates and best-corrected visual acuity was not significant ($r=-0.20$; $P=.29$).

Incorrect response rates were similar among the 3 monocular viewing conditions, including 28% (10%) during amblyopic eye viewing, 28% (9%) during fellow eye viewing, and 26% (10%) during normal eye viewing

($F_{2,24}=0.53$; $P=.60$). However, a significant difference in no response rates was found: 13% (10%) during amblyopic eye viewing, 10% (9%) during fellow eye viewing, and 7% (5%) during normal eye viewing ($F_{2,24}=5.39$; $P=.01$). Again, there was a significant decrease in no response rates from viewing in amblyopic eyes to fellow eyes to normal eyes ($F_{1,24}=10.49$; $P=.004$).

A comparison of mean reaction times showed no differences among the 3 monocular viewing conditions: 2.7 (0.5) seconds during amblyopic eye viewing, 2.6 (0.5) seconds during fellow eye viewing, and 2.6 (0.4) seconds during normal eye viewing ($F_{1,24}=0.13$; $P=.86$).

Binocular Viewing

During binocular viewing, a significant difference in correct response rates was found between amblyopic patients (58% [8%]) and visually normal participants (68% [10%]; $F_{1,65}=5.02$; $P=.03$). There were no differences in any of the other performance measures (incorrect responses, no responses, and mean reaction time) between the amblyopic patients and visually normal participants.

Subgroup analysis showed no significant differences in any of the 4 performance measures among different amblyopia subtypes during monocular or binocular view-

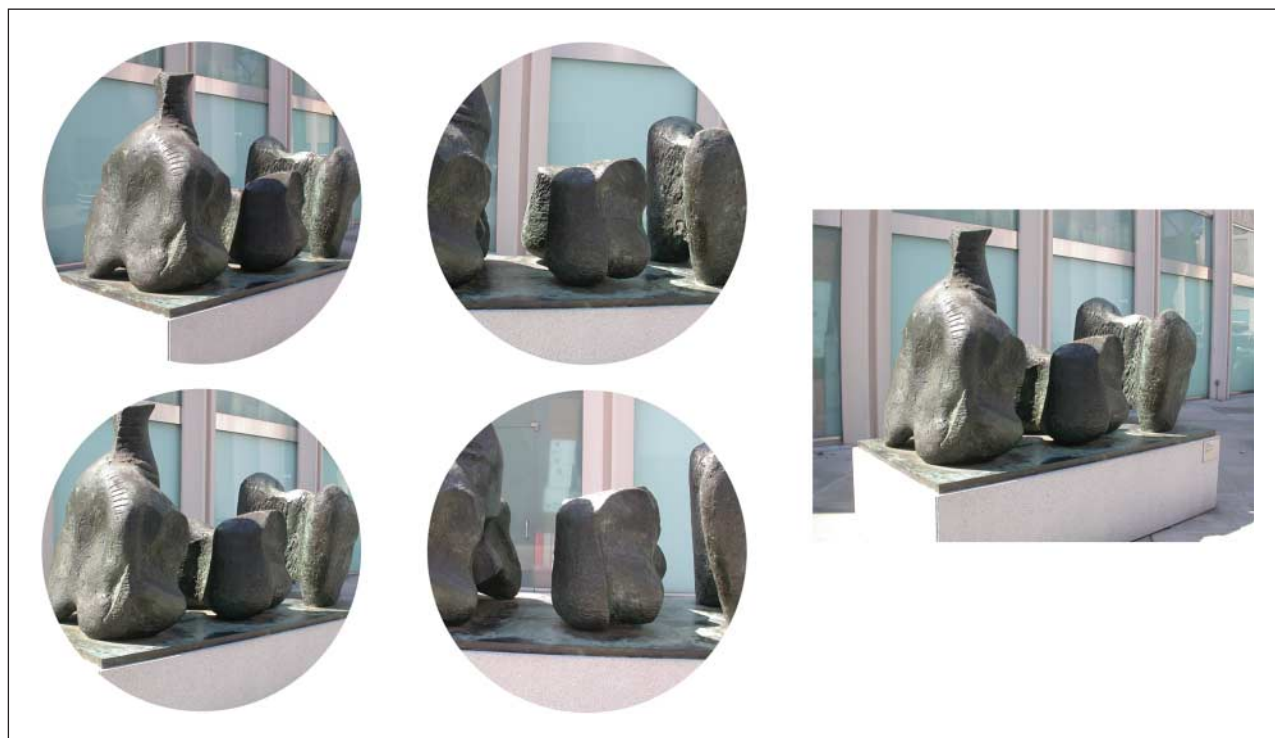


Figure 2. Each trial consisted of a reference image displayed on the right side of the screen subtending a visual angle of 8°. Simultaneously, on the left side of the screen, 4 choices were shown in a 2 × 2 array, each within a circular aperture that was 5° in diameter. One of these 4 choices was identical to the reference image, whereas the other 3 resembled the reference image but were not identical to it. In this particular trial shown, the choice at the lower left was identical to the reference image on the right, and an overall correct response rate of 57% was obtained across all participants.

ing, which may be a result of the small sample size in each subtype.

PERFORMANCE BY TREATMENT OUTCOMES

The mean rates of correct, incorrect, and no responses for the 2 treatment outcomes of amblyopic and normal eyes are shown in **Figure 4**. A significant difference in correct response rates was observed at 59% (10%) in the unsuccessfully treated group, 64% (6%) in the successfully treated group, and 67% (10%) in the visually normal group ($F_{2,24}=7.09$; $P=.002$). There was a significant increase in the percentage of correct rates from the unsuccessfully treated group to the successfully treated group to the visually normal group ($F_{1,24}=14.10$; $P<.001$).

Incorrect response rates were similar among the 3 groups, at 29% (9%) in the unsuccessfully treated group, 26% (6%) in the successfully treated group, and 26% (9%) in the visually normal group ($F_{2,24}=0.97$; $P=.38$). However, a significant difference in no response rates were found: 12% (10%) in the unsuccessfully treated group, 10% (7%) in the successfully treated group, and 7% (5%) in the visually normal group ($F_{2,24}=5.22$; $P=.008$). Again, there was a significant decrease in no response rates from the unsuccessfully treated group to the successfully treated group to the visually normal group ($F_{2,24}=10.43$; $P=.002$).

A comparison of mean reaction times showed no differences among the 2 treatment outcomes of amblyopic and normal eyes at 2.6 (0.5) seconds in the unsuccessfully treated group, 2.8 (0.5) seconds in the successfully treated group, and 2.6 (0.4) seconds in the visually normal group ($F_{1,24}=1.63$; $P=.26$).

COMMENT

In previous studies⁹⁻³⁴ of visual deficits in amblyopia, certain predetermined aspects of visual function (eg, acuity, contrast sensitivity, and global contour processing) were tested by using stimuli specifically designed for use in the laboratory. In this study, we endeavored to broaden the scope of amblyopia research by investigating whether perception of images of real-world scenes is also affected in amblyopic patients during a match-to-sample task. We found that patients with amblyopia performed significantly worse than visually normal participants, with lower correct response rates during amblyopic eye viewing than during fellow eye viewing. The poor performance remained when amblyopic patients were tested binocularly. In addition, the difference in performance among viewing eyes was not due to a difference in visual acuity. To the best of our knowledge, this is the first study to document visual dysfunction during viewing of images of real-world scenes in amblyopia.

Some amblyopia treatment studies³⁸⁻⁴³ have defined success as the attainment of a visual acuity of 20/30 or 20/40 by the end of the treatment period, whereas others⁴⁴⁻⁴⁸ have adopted a more strict criterion of 20/20 or 20/25 (normal or near-normal visual acuity) as their definition of success. We defined treatment success using the latter, more stringent criteria for 2 reasons. First, from a functional viewpoint, the best condition that promotes normal binocular visual development is when the visual input from each eye is equal.⁴⁹ Second, by using the same visual acuity criterion for successfully treated patients and

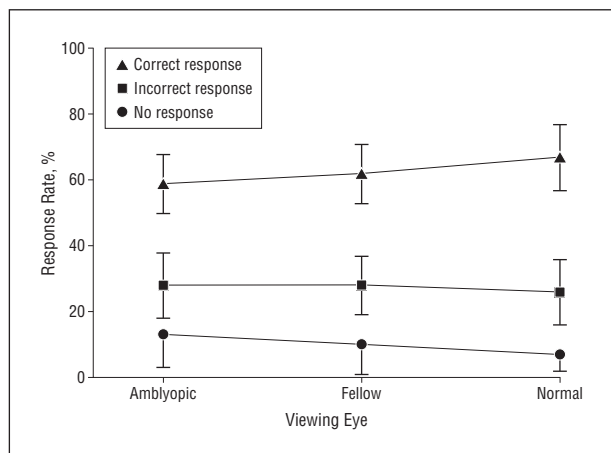


Figure 3. Performance by viewing eye showing the mean rates of correct, incorrect, and no responses during viewing with amblyopic, fellow, and normal eyes. Error bars represent 1 SD.

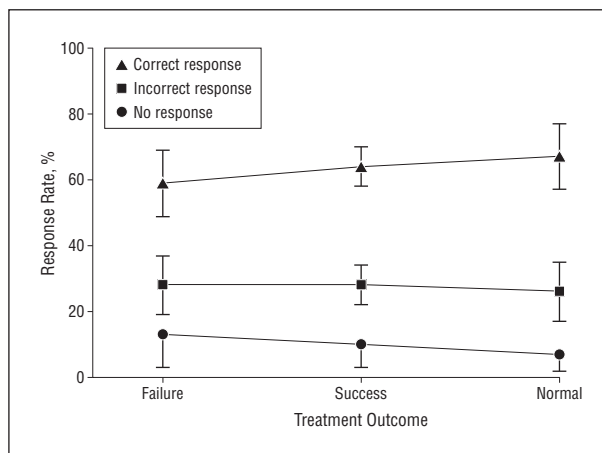


Figure 4. Performance by treatment outcomes of the amblyopic eye showing the mean rates of correct, incorrect, and no responses in the unsuccessfully treated, successfully treated, and normal groups. Error bars represent 1 SD.

visually normal participants, we ensured that any difference in performance between successfully treated and normal eyes was not due to a difference in their visual acuity. We found that perception of images of real-world scenes in the successfully treated eye was significantly worse than in the normal eye. Our results provide support that visual deficits other than high-contrast visual acuity remained despite achievement of normal to near-normal visual acuity after current amblyopia therapy.

It has been proposed that, during binocular viewing, the inputs from both eyes contain correlated stimulus signals and that they summate during visual processing, whereas the noise signals in the stimulus from each eye are uncorrelated, effectively canceling each other out. As a result, the signal to noise ratio in the stimulus signals increases during binocular viewing, which, in turn, leads to better visual performance.⁵⁰ However, this binocular advantage was not evident in patients with amblyopia, as indicated by the observation that their performance during binocular viewing was no better than that during amblyopic eye viewing. This may be due to a disruption of binocular organization and a loss of binocularity in neurons in the visual cortex in amblyopia.⁵¹⁻⁵⁴ However, a recent study demonstrated that binocular summation of contrast sensitivity is normal in people with strabismic amblyopia, when stimulus contrast is adjusted to equalize visibility of the gratings for the 2 eyes,⁵⁵ suggesting that the binocular summation deficits seen in previous studies^{54,56-61} may result from interocular differences in contrast sensitivity between the eyes.

Visual processing is generally believed to be divided into the dorsal (the “where” or magnocellular) and ventral (the “what” or parvocellular) pathways. Visual information enters the ventral pathway through the primary visual cortex (V1), projecting through V2 and V4 to the inferior temporal cortex. The ventral pathway is believed to be primarily concerned with object recognition through integrating features,⁶² and it is also responsible for detection of second-order motion (including spatiotemporal scene variation of contrast and depth but not luminance) and biological motion.^{63,64} Global visual tasks fall generally into 1 of 2 categories. The first is feature

integration, a process during which adjacent elements in the visual field are identified and grouped as belonging to the same object.^{15,65,66} The second is image segregation, a process during which an object is identified as a whole and parsed from its background.⁶⁷ Patients with amblyopia have deficits in feature integration^{13,15,66} and image segregation tasks.⁶⁸⁻⁷⁰ In addition, crowding or spatial interference is a well-documented characteristic of amblyopia^{28,71,72} that involves detection of simple features and feature integration.^{73,74} There is an ongoing debate, however, as to whether these deficits in higher-level global visual function in amblyopia are a result of abnormal processing in extrastriate areas that are affected directly by early abnormal visual experience, whether these deficits are a cascade downstream effect resulting from poor, suboptimal visual inputs from early visual areas, or whether they are both.^{15,66} These deficits in global visual tasks remain abnormal in amblyopia even after visual acuity and contrast sensitivity deficits have been taken into account,^{15,66} indicating that these deficits occur primarily in extrastriate areas and are independent of abnormal inputs from V1.

Although the results of our current study demonstrated that perception of images of real-world scenes is affected in patients with amblyopia, what remains to be elucidated is whether these abnormalities in real-world scene perception are associated with deficits in acuity and other lower-level visual processes or are associated with higher-level perceptual deficits. In people with normal vision, factors such as contrast gain control⁷⁵ and other image statistics⁷⁶⁻⁸¹—processes that occur primarily in V1⁸²⁻⁸⁴—are important for contour and feature detection of objects during real-world scene perception. Contrast gain control describes the responses of a V1 neuron that could be modulated by contrast or orientation outside its classic receptive field.⁷⁵ For example, a neuronal response is enhanced if nearby lines of similar contrast and orientation are identified as belonging to the same edge.⁷⁵ Contrast gain control plays a major role in determining how easily an object is identified, by normalizing across contrast levels of an image, thereby allowing edge or feature detection among many objects of differing contrasts.⁷⁵ Other image statistics, such

as local similarities in orientation and spatial frequency content, are also important for contour and feature detection.⁷⁶⁻⁸¹ Analyses of the statistical properties of real-world images have demonstrated that the orientations of nearby contours are highly correlated with one another and that there is a high collinearity in the contours and edges belonging to the same edge or object.⁸¹ Single-cell responses in neurons in V1 of animals^{82,83} and behavioral performance in humans^{76,85,86} suggest that the visual system has evolved to use these statistics for feature extraction.

Effective real-world scene perception is also dependent on processes that occur in areas beyond V1. Processes that are related to boundary and edge detection of textures and objects have been identified in cats and primates as early as areas analogous to the human V2.^{87,88} Primate single-cell and human imaging studies have identified areas related to object perception in the V3A area and lateral occipital cortex⁸⁹⁻⁹² and extending into the inferior temporal cortex.^{91,92} In addition, people with normal vision are very efficient at extracting categorical information from complex real-world scenes (eg, detecting the presence of object categories such as plants or furniture)^{77,93-95} despite the fact that different classes of real-world scenes often share similar image statistics.⁹⁶ Recent studies using functional magnetic resonance imaging have shown that the parahippocampal place area, retrosplenial cortex, and lateral occipital complex all contribute to real-world scene categorization by humans.^{96,97}

It is possible that the deficits that we demonstrated in this pilot study are related to disruptions of visual processing in V1; the early extrastriate areas; the cortex specialized for objects (lateral occipital cortex), scenes (parahippocampal place area), and faces (fusiform face area); or a combination of these areas. Accumulating research suggests that higher-order tasks that require attention, above and beyond the influence of deficits attributable to V1, are also affected in amblyopic patients.²⁴⁻²⁶ Further studies using real-world scene perception paradigms adapted from studies of visually normal participants (eg, free recall, forced-choice recognition, visual priming paradigms, and paradigms with variable stimuli presentation time and a shorter time window for response)^{77,86,98-102} will shed light on this issue. Neuroimaging with high temporal (eg, magnetoencephalography) and spatial (eg, functional magnetic resonance imaging) resolution^{96,97,103,104} will further clarify the relative role of lower- and higher-level visual processing in contributing to the deficits in real-world scene perception in amblyopia.

In summary, this is the first study to demonstrate that people with amblyopia have impaired perception of images of real-world scenes. In addition, our findings provide support that visual functions other than high-contrast visual acuity remain deficient despite successful amblyopia therapy using clinical criteria. Together with the growing evidence that people with amblyopia often have poor motor performance and eye-hand coordination,¹⁰⁵⁻¹⁰⁸ our results show that amblyopia affects many aspects of a person's everyday life, including perception of real-world scenes. Clinicians should be aware of these deficits when providing counseling to patients and their parents.

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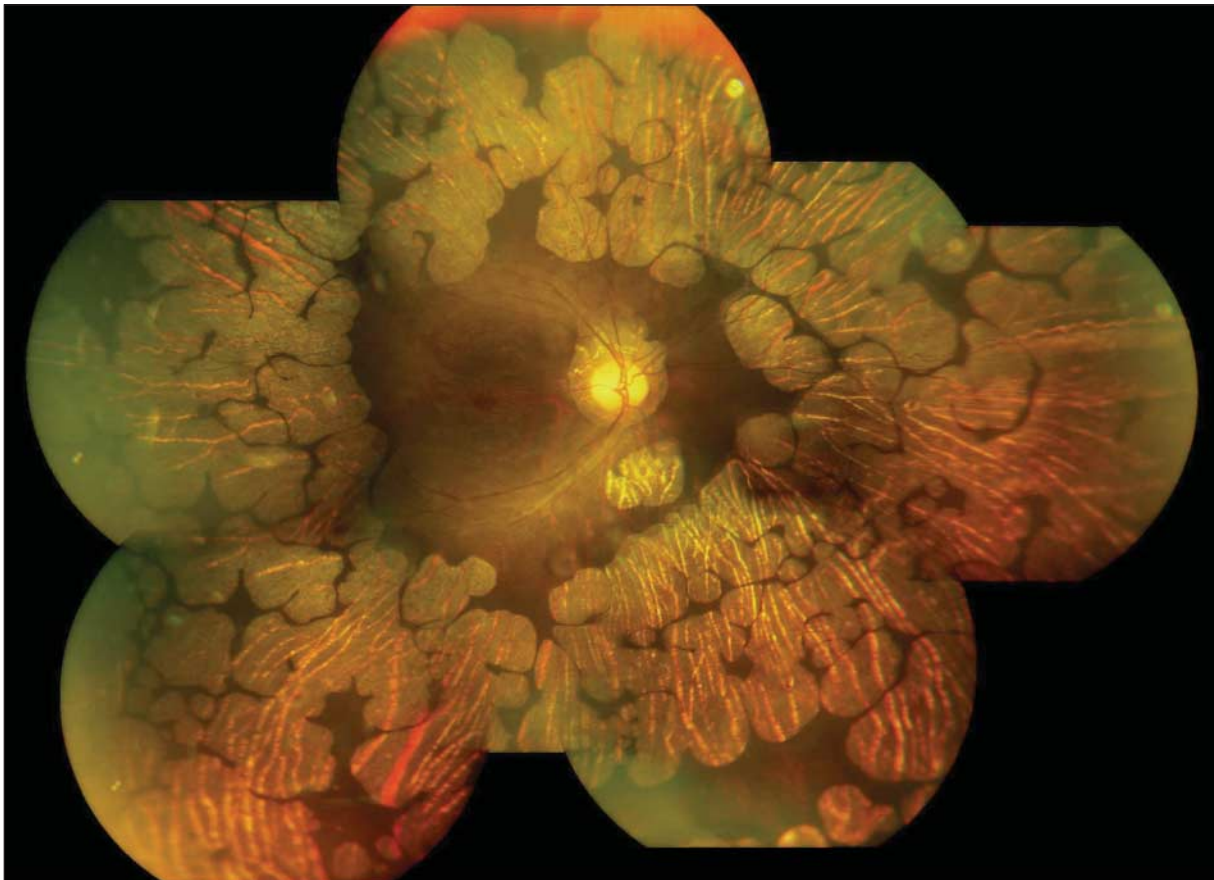
Ophthalmic Images

Gyrate Atrophy in a Young Man

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A 17-year-old man presented with night blindness. On examination, fundus photography revealed large peripheral paving stone-like areas of atrophy of the retinal pigment epithelium and choriocapillaris, with characteristic scalloped border. A clinical diagnosis of gyrate atrophy was made. The patient was advised to use sight-enhancement devices.