Amblyopic contrast sensitivity: insensitivity to unsteady fixation

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Functional amblyopia (a typically unilateral loss of visual acuity of unknown origin) is frequently accompanied by unsteady fixation. Measurements taken under conditions of retinal-image stabilization indicate that this fixation problem does not contribute to the currently measured losses in spatial contrast sensitivity of the amblyopic eye. Indeed, retinal image motions recorded from unsteadily fixating eyes do not produce spatial contrast sensitivity losses when superimposed on the central field of a normal subject, indicating that such losses are not an immediate consequence of unsteady fixation. (INVEST OPHTHALMOL VIS SCI 23:113-120, 1982.)

Key words: amblyopia, spatial contrast sensitivity, eye movements, unsteady fixation, eccentric fixation

Functional amblyopia is generally defined in terms of a measured sensory loss, i.e., a typically unilateral loss in visual acuity attributable to neither any known pathologic condition nor to the presence of an uncorrected refractive error at the time of testing. In addition, amblyopia represents one of several visual anomalies that are either defined or accompanied by an abnormal eye-movement pattern. The frequently unsteady and/or eccentric fixation that is characteristic of amblyopic eyes has presented a perennial obstacle to the unambiguous interpretation and assessment of amblyopic visual performance. Control of both components of such anomalous fixation patterns is important not only for determining whether a measured loss reflects primarily a sensory or a motor problem but also for an understanding of the possible contribution of such anomalous fixation patterns to the development of such losses.

In the case of amblyopic spatial contrast sensitivity deficits, Hess has argued that an anomalous eye-movement pattern should not "detrimentally affect contrast thresholds for amblyopes at any frequency" (p. 236). This was based on (1) his finding that the amblyopic/normal eye cutoff spatial frequency ratio for stabilized-image conditions (derived from the duration visibility of the afterimage of a square-wave grating) was similar to that obtained for extrapolations from unstabilized contrast thresholds for cathode ray tube (CRT)-generated gratings, and (2) a then-justifiable assumption that the amblyopic eye-movement anomaly was confined to the saccadic component. The latter finding suggested that only the cutoff frequency region need be examined. However, recent reports indicating abnormally high drift velocities in amblyopic eyes and the importance of drift velocity for overall contrast...
sensitivity\textsuperscript{12} point to the need for examining the effect of amblyopic eye movements across a broad range of spatial frequencies. Further, the marked variation between subjects in the stabilized/unstabilized ratio for a given eye\textsuperscript{10} argues for the need for a technique (e.g., forced-choice) involving a constant-criterion comparison and the same stimulus display. Experiment I of this study evaluates the contribution of unsteady amblyopic fixation by comparing overall spatial contrast sensitivity under both stabilized and unstabilized image conditions.

The mere stabilization of the retinal image in an amblyopic eye, however, is not an adequate technique for addressing the second issue—the possible contribution of unsteady fixation to the development of amblyopia. Specifically, since there is considerable evidence that the central field of amblyopic eyes is scotomatous,\textsuperscript{13,14} stabilizing a redundant stimulus display such as a grating in an already-deficient eye would not necessarily be expected to produce any improvement in vision. Although it is likely that an erratic fixation pattern might develop secondary to a central field loss, it is also conceivable that a sufficiently erratic pattern might "smear" the retinal image and thus generate a local deprivation that later could lead to a central field loss. In the latter case, one should be able to simulate amblyopic contrast sensitivity losses in the central field of a normal eye by stabilizing the retinal image and then superimposing image motions such as would be produced by an unsteadily fixating amblyopic eye. This is the subject of Experiment II. Alternatively, the failure of these anomalous eye movement patterns to produce a sensitivity loss would provide further evidence for the previously noted resilience of contrast sensitivity\textsuperscript{15} and visual acuity\textsuperscript{16} to the effect of retinal-image motion.

Subjects

Four normal and four amblyopic subjects were tested in the various phases of these experiments. Only the right eye was tested in each case because of limitations in the optical system used. All normal subjects had corrected or uncorrected visual acuities of at least 20/20. All amblyopes were right-eyed amblyopes. The first (A1), a 29-year-old woman, was a 10° right esotrope (OD = 2.00 -0.75 × 170°, OS = -6.75 -1.25 × 15°) with acuities of 20/80 and 20/20, respectively. The second (A2), a 25-year-old man, was an anisometropic amblyope (OD = -11.00 -3.00 × 170°, OS = -2.75 -1.25 × 167°) with acuities of 20/200 and 20/20, respectively. The third (A3), a 15-year-old male, was a microtrope (OD = +3.25 -0.25 × 30°, OS = -0.5 sph.) with acuities of 20/60 and 20/15, respectively. The fourth (A4), a 29-year-old man, was an anisometropic amblyope (OD = +5.25 -4.00 × 90°, OS = -2.75 sph) with acuities of 20/60 and 20/15, respectively. All four amblyopic subjects were originally referred as having predominantly central but unsteady fixation. However, measurements with the entoptic Haidinger brush phenomenon indicated that amblyopes A1 and A3 eccentrically fixated by approximately 1.5° to 2.0° and 0.5°, respectively. Accordingly, control conditions were included in both experiments to rule out eccentric fixation as an explanation for the major findings described here. Further, one normal and one amblyopic subject (A1) were retested under cycloplegic conditions to rule out possible fluctuations in accommodation as contributing to the major trends reported in Experiment I. All results reported in Experiment II were obtained with the normal subject under cycloplegic conditions.

Experiment I

Methods. A right-eyed version of the SRI Double Purkinje-image Eyetracker Image Stabilization System\textsuperscript{17,18} was used to compare unstabilized with stabilized spatial contrast sensitivity. CRT-generated sine-wave gratings of eleven different spatial frequencies were presented in random order, using a modified version of the two-alternative, temporal, forced-choice psychophysical procedure.\textsuperscript{19} The subject's task was to indicate in which of two 800 msec intervals (separated by 300 msec) a grating was presented. To avoid temporal transients, the rise and decay phases of grating presentation lasted 100 msec each and followed a Gaussian time course. With the exception of the top dashed function in Fig. 3, A, and the solid line in Fig. 3, C (which were based on 50 presentations/frequency), each of the remaining forced-choice data points in Figs. 2 and 3, A and C, represents a 71% correct level of detection determined from at least 100 presentations/frequency. The stimulus field was viewed through an 2.5 mm
artificial pupil, subtended 2°, had an average luminance of 3.4 foot lamberts and appeared optically superimposed on the cross-shaped array of five fixation points described in connection with Fig. 1.

To ensure accurate image stabilization, each subject adjusted the gain of the signal to the eyetracker mirrors with a procedure that involved comparing the motion of a stabilized target against the unstabilized array of fixation lights. To set the horizontal gain, for example, each subject viewed a vertically oriented 120 by 6 min arc bar (produced by masking the CRT screen) and adjusted the gain until the stabilized bar moved by an appropriate amount as the subject shifted fixation from the right to left source in the array. Rotation of the stabilized bar by 90° then permitted a similar adjustment for the vertical gain. To provide an independent check on the accuracy of the eyetracker gain-setting procedure used, one normal and two amblyopic subjects set continuously exposed gratings to threshold under both stabilized and unstabilized viewing conditions using a method of adjustment. Subjects were allowed 15 sec to adjust each spatial frequency to a near-threshold visibility level with a 10-turn attenuator. They were then required to continuously track grating visibility for an additional 15 sec, indicating their final threshold setting at the end of this period. Thresholds were computed from the average of at least four threshold settings/frequency.

Insofar as the gains are set properly, image stabilization should produce the expected fading of continuously exposed stimuli with the consequent loss in contrast sensitivity.

**Results.** Fig. 1 compares the fixation patterns recorded from one normal and two amblyopic eyes (A1 and A2) under two viewing conditions. Differences between the normal and amblyopic patterns are readily evident. In the context of the subsequent discus-
Forced-choice contrast sensitivity functions for the three eyes represented in Fig. 1 are summarized in Fig. 2. It is evident that retinal-image stabilization produces no significant change in contrast sensitivity for either the normal or the amblyopic eye. These data suggest that the unsteady fixation of these amblyopic eyes does not contribute to their currently measured loss in spatial contrast sensitivity. Further, these data also suggest that grating resolution by the amblyopic eye occurs within the first few tenths of a second, as has been reported for the normal eye.\textsuperscript{21}

Since two subjects showed small amounts of eccentric fixation, it was necessary to determine the possible contribution of this factor to the sensitivity losses. Accordingly, subject A1, having the largest eccentric fixation, was retested under stabilized conditions wherein the CRT display was offset to compensate for her eccentric fixation. The resulting forced-choice function was within ±1 S.E.M. of her original stabilized function, which appears in Fig. 2. This finding rules out eccentric fixation as an explanation for her marked loss in sensitivity. Further evidence against eccentric fixation as an explanation of the losses observed in these amblyopic eyes is provided in connection with Experiment II (see Fig. 3, C).

Fig. 3, A, provides a summary description of the loss in forced-choice contrast sensitivity under unstabilized viewing conditions for the four amblyopic eyes studied. This loss is specified relative to the contrast sensitivity of the normal eye of the normal subject under the same viewing conditions, represented here as the "zero" baseline. The use of the right eye of the normal subject as a baseline is justified by the previous finding that the normal eyes of amblyopic subjects demonstrate normal spatial contrast sensitivity\textsuperscript{7} and by the observation that data from the (right) eyes of three other normal subjects did not differ significantly from that of the normal subject measurement period. It is evident that fixation in this "worst-case" amblyopic eye is, although erratic, generally confined to a range of about 1.5° to 2.0°, i.e., a range approximating the 2° subtense of the grating display used to measure contrast sensitivity.

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Fig. 3. A, Differences in contrast sensitivity for the amblyopic vs. normal eye measured with the forced-choice procedure. Circles and triangles, Loss in unstabilized contrast sensitivity for the 20/80 (A1) and 20/200 (A2) amblyopic eyes, respectively, referred to in Fig. 1 and measured relative to that of the normal eye of the normal subject (open diamond baseline). Dashed functions represent losses in unstabilized contrast sensitivity for two additional amblyopes used in various phases of this research. Note that ±1 S.E.M. generally ranged from about 0.2 to 0.3 log units in Figs. 2 and 3. B, Loss in stabilized contrast sensitivity measured with the method of adjustment for the normal eye (solid line) and two amblyopic eyes (A1, circles; A4, squares). The zero baseline represents the unstabilized threshold for the respective subjects. C, Attempted forced-choice simulation of amblyopia. Changes in contrast sensitivity produced in the normal central field by superimposing retinal image motions (vertical and horizontal) previously recorded from A1 (circles) and A4 (squares) are shown. The zero baseline refers to a "self-stimulation" control (dashed function in Fig. 2), the retinal-image motions of which were produced by playing back the normal subject’s own eye movement pattern. Solid line, Loss in unstabilized contrast sensitivity for the normal eye produced by decentering the CRT display 2.5° into the inferior field. D, Attempted simulation of amblyopia using the method-of-adjustment. Circles, Change in contrast sensitivity produced in the normal central field using the eye movement pattern recorded from the 20/80 amblyope (A1) are shown. The baseline again is the control condition in which the normal subject’s own eye movement pattern was used.

Fig. 3, B, compares the difference in unstabilized and stabilized thresholds for the normal and two amblyopic eyes obtained by the method of adjustment. These results are important insofar as they exclude the possibility that the lack of improvement in amblyopic contrast sensitivity under stabilized forced-choice conditions was caused by inadequate eyetracker gain settings and hence...
Fig. 4. Variation in horizontal eye position during attempted steady fixation of the CRT display used for contrast sensitivity measurement. N, Normal eye. The vertical section of the calibration trace appearing at the bottom of this figure represents 1°, and the horizontal bar denotes 5 sec.

Experiment II

Method. To evaluate the effect of retinal-image motions produced by unsteadily fixating amblyopic eyes on contrast sensitivity in a normal central field, a two-channel FM tape recorder (calibrated for unity gain) was used to record horizontal and vertical eye movements from the normal subject and from three amblyopic eyes while each subject was attempting to maintain steady fixation on the CRT screen. Forced-choice contrast sensitivity was then measured in the central field of the normal eye while electronically adding the horizontal and vertical eye movement signals required for image stabilization to the respective eye-movement signals previously recorded from each of the four subjects. Signals were added by means of two independent, unity-gain, noninverting operational amplifiers.

To characterize differences between the normal vs. amblyopic fixation patterns used in these attempted simulations of amblyopic fixation, two 15 sec samples of the recorded horizontal eye movement patterns were analyzed for each subject. One sample was taken from the beginning, and a second sample was taken from the end of the approximately 5 to 6 min of fixation recorded for each subject. A sampling procedure similar to that described by Nachmias was used for calculation of means of two independent, unity-gain, noninverting operational amplifiers.

Results. Fig. 4 illustrates a sample of the horizontal component of the fixation pattern for the normal eye of the normal subject and from each of three amblyopic eyes. Saccade frequency in the amblyopic eyes ranged from 1.6/sec (A3) to 2.7/sec (A1). Although these values are higher than that for the normal eye (1.2/sec) used here, they can probably be considered to be within normal limits. Ditchburn estimates the normal range of saccade frequency to be 0.6 to 2.3/sec. As is evident from Fig. 4, however, saccade amplitudes were generally larger in the amblyopic eye than in the normal eye. Mean drift velocity was also higher in the amblyopic eyes, ranging from a low of 0.157/sec for A4 to a high of 0.377/sec for A1 and compared with a velocity of 0.08°/sec for the normal eye. The results of this comparison of the normal vs. amblyopic eye fixation pattern are similar to those reported previously.

The dashed function in Fig. 2 represents a baseline function for assessing the effect of amblyopic fixation patterns on central field contrast sensitivity of the normal eye. This function represents the loss in contrast sensitivity for the normal observer when his own eye movement pattern was played back from the tape recorder. The loss depicted here, however, is not the result of retinal-image motions produced by this subject’s own eye movements, since a quantitatively similar decrement in sensitivity was produced by the playback of a recorded D.C. potential (simulating a perfectly stationary eye). This loss re-
fleets, rather, residual noise in the recording system, which although small in amplitude (as illustrated by the samples in Fig. 4), was sufficient to produce a decrement in sensitivity toward the higher spatial frequencies. Consequently, the changes in contrast sensitivity caused by amblyopic fixation patterns described in Fig. 3, C, were measured relative to the noise-limited "self-stimulation" control condition in which the normal subject's own eye-movement pattern was played back.

The open circles and squares in Fig. 3, C, indicate the change in forced-choice contrast sensitivity for the same normal subject, produced by the eye-movement patterns recorded from A1 and A4, respectively. Quantitatively similar results were obtained from the eye-movement pattern recorded from the third subject, A3. From Fig. 3, C, it is evident that there is little loss in central field contrast sensitivity produced by the difference in the steadiness-of-fixation represented by the normal vs. amblyopic eyes. Moreover, the failure to find any loss cannot be due to a saturation effect. If the combination of recorder noise and normal eye movements were sufficient to produce a maximal loss in sensitivity, this would have precluded measurement of any additional loss produced by the amblyopic fixation patterns. However the "self-stimulation" baseline represented by the dashed function in Fig. 2 is only slightly depressed at the higher spatial frequencies and would have provided ample opportunity to observe any additional loss produced by the amblyopic fixation patterns.

Results represented by the solid line in Fig. 3, C, provide a further indication that an eccentric fixation hypothesis alone is not adequate to explain the sensitivity losses in these amblyopic eyes. This function shows the loss in forced-choice contrast sensitivity of the normal eye when the CRT display was positioned 2.5° into the inferior field. Although this particular function represents the difference between unstabilized central (the zero baseline) and eccentric sensitivities, stabilized-image estimates of this loss were quantitatively similar, as were estimates obtained at comparable eccentricities in other quadrants. It is obvious that eccentric fixation (in contrast to unsteady fixation) can produce significant losses in contrast sensitivity. However, eccentric fixation is not sufficient to explain the measured losses for the amblyopic eyes in Fig. 3, A, since, as previously noted, the largest eccentric fixation observed was 1.5° to 2.0°.

Finally, Fig. 3, D, indicates that the results of Experiment II were not specific to the use of the forced-choice test procedure. Here contrast sensitivity was measured by the method-of-adjustment and continuously exposed gratings. The zero baseline again refers to a "self-stimulation" control condition using the normal subject's own fixation pattern.

Discussion

These results indicate that retinal-image motions produced by unsteady fixation of amblyopic eyes do not contribute significantly to their losses in spatial contrast sensitivity. In addition, since superimposition of retinal-image motions from unsteadily fixating amblyopic eyes on the central field of a normal subject produced no immediate loss in contrast sensitivity, it seems unlikely that unsteady fixation contributes significantly to the development of a currently measured loss. These results afford support for the view that the amblyopic central field is scotomatous and that grating resolution is as resilient to retinal image motion in amblyopes as it is in normals.

Notwithstanding the present findings, there are clinical instances (e.g., latent nystagmus) in which visual acuity measured with punctate targets is reportedly improved by a drug-induced attenuation of an anomalous eye-movement pattern. One possibility is that such findings point to the importance of stimulus size and redundancy. It is possible, for example, that an unsteady amblyopic fixation pattern would be manifestly more deleterious if vision were tested with small punctate acuity targets instead of a redundant grating display.

Alternatively, it is possible that such a finding reflects differences in "image stabilization" technique, i.e., optical compensation.
for a naturally occurring erratic fixation pattern vs. attenuation of the erratic fixation pattern. The present experiments indicate that the retinal-image motions produced by unsteadily fixating amblyopic eyes are neither sufficient to explain their currently measured losses in contrast sensitivity nor to produce a loss in contrast sensitivity in the normal central field. Whereas these experiments did not test the possibility that contrast sensitivity might be improved with attenuation of the erratic fixation pattern, such a result would be significant insofar as it would imply that the oculomotor system could play an important role in setting the time-average sensitivity of the visual system. In this regard, it should be noted that H. Bedell and M. C. Flom (personal communication) have found cases in which contrast sensitivity is apparently improved in amblyopic eyes when steady foveal fixation is maintained by auditory feedback.

We thank Drs. W. Boger, III, D. Miller, I. Mohindra, D. Nadler, A. Moskowitz, S. Sokol, and Mr. R. J. Ellis for their assistance in the various phases of this research, and Drs. M. Clarke, F. M. de Monasterio, T. Piantanida, and C. Schor for their helpful comments and criticisms of an earlier version of this article. We also thank our subjects, whose collaboration made this research possible.

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