Psychophysical investigations of the temporal modulation sensitivity function in amblyopia: uniform field flicker

Ruth E. Manny and Dennis M. Levi

The temporal modulation sensitivity function was studied in eight strabismic and/or anisometropic amblyopes and in two subjects with amblyopia resulting from monocular stimulus deprivation (cataract and ptosis). Half of the strabismic/anisometropic amblyopes showed a reduction in the sensitivity of the amblyopic eye. These differences were more marked at low and middle temporal frequencies. Two strabismic/anisometropic observers showed little difference in sensitivity between the two eyes, but in the remaining two observers the amblyopic eye was slightly more sensitive to low-frequency modulation than was the nonamblyopic eye. Four of the strabismic/anisometropic amblyopes also showed a small (5% to 10%) but statistically significant difference in the critical fusion frequency, with the sensitivity of the amblyopic eye being reduced. These differences in sensitivity were not related to the visual acuity loss. However, all differences in sensitivity between the two eyes were reduced or eliminated when the mean luminance of the test field was decreased by 2 log units from 32 to 0.32 cd/m², or with suprathreshold stimulation. One of the two stimulus-deprivation amblyopes showed a decrease in sensitivity to low and middle temporal modulation frequencies similar to that found in four of the strabismic/anisometropic amblyopes, and the other observer showed a marked decrease in sensitivity at all temporal frequencies. The losses in temporal resolution of the amblyopic eye in both strabismic/anisometropic and stimulus-deprivation amblyopia are small in comparison with those reported in the spatial domain. (INVEST OPHTHALMOLOG VIS SCI 22:515-524, 1982.)

Key words: temporal modulation sensitivity function, de Lange function, amblyopia, critical fusion frequency, magnitude estimation, psychophysics

Clinically, functional amblyopia is characterized by a decrease in visual acuity that is not improved with proper optical correction and that is not associated with any observable organic defect. This decrease in spatial resolution at photopic levels has been found to extend over a wide range of spatial frequencies.1-5 Although the spatial properties of amblyopic eyes have received a great deal of attention recently, the defect in amblyopia does not appear to be limited to spatial resolution. Abnormalities in ocular motility,6-8 accommodation,9 and pupil response10 have also been reported. Despite these and numerous other investigations, comparatively little is known about the temporal resolving capacities of an amblyopic eye. Critical fusion frequency (CFF) has been studied, and although reports are conflicting,11-13 it appears that CFF may be slightly decreased in the amblyopic eye when compared with...
Table I. Visual characteristics of amblyopic subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age/sex</th>
<th>Eye</th>
<th>Visual acuity</th>
<th>CFF</th>
<th>Refraction</th>
<th>Fixation (AE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D.B.</td>
<td>34/F</td>
<td>OD</td>
<td>20/15</td>
<td>*50.0 ± 1.59</td>
<td>plano</td>
<td>Unsteady central</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/15</td>
<td>45.0 ± 1.01</td>
<td>+4.75-1.75 × 0.15</td>
<td></td>
</tr>
<tr>
<td>B.J.</td>
<td>23/F</td>
<td>OD</td>
<td>20/15-4</td>
<td>*45.4 ± 0.89</td>
<td>plano</td>
<td>Unsteady 1/2 to 1° superior and nasal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/34</td>
<td>41.0 ± 0.00</td>
<td>+4.0-1.25 × 110</td>
<td></td>
</tr>
<tr>
<td>S.K.</td>
<td>30/F</td>
<td>OD</td>
<td>20/15</td>
<td>*52.2 ± 1.79</td>
<td>plano</td>
<td>Unsteady 1° nasal and inferior</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/50</td>
<td>47.6 ± 0.89</td>
<td>-0.25-1.25 × 175</td>
<td></td>
</tr>
<tr>
<td>L.H.</td>
<td>23/F</td>
<td>OD</td>
<td>20/104</td>
<td>45.6 ± 1.14</td>
<td>+2.00-1.25 × 175</td>
<td>Unsteady 2° nasal and inferior</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/15</td>
<td>43.6 ± 0.54</td>
<td>-1.25-0.50 × 140</td>
<td></td>
</tr>
<tr>
<td>J.V.</td>
<td>25/M</td>
<td>OD</td>
<td>20/20</td>
<td>50.2 ± 0.63</td>
<td>+0.75-0.25 × 070</td>
<td>Unsteady 1° nasal and superior</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/60</td>
<td>52.2 ± 1.92</td>
<td>+4.50-0.50 × 023</td>
<td></td>
</tr>
<tr>
<td>R.C.</td>
<td>33/M</td>
<td>OD</td>
<td>20/67</td>
<td>42.2 ± 0.84</td>
<td>pl-0.50 × 150</td>
<td>2°-3° nasal (estimated)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/15</td>
<td>42.4 ± 1.52</td>
<td>pl-0.25 × 110</td>
<td></td>
</tr>
<tr>
<td>B.W.</td>
<td>30/M</td>
<td>OD</td>
<td>20/20*</td>
<td>*45.6 ± 0.54</td>
<td>pl-0.50 × 120</td>
<td>Unsteady 2°-3° nasal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/36</td>
<td>42.2 ± 1.64</td>
<td>+1.00-1.00 × 090</td>
<td></td>
</tr>
<tr>
<td>C.W.</td>
<td>28/F</td>
<td>OD</td>
<td>20/153</td>
<td>46.6 ± 1.52</td>
<td>plano</td>
<td>Unsteady 1° temporal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/20-3</td>
<td>45.0 ± 0.00</td>
<td>plano-0.25 × 070</td>
<td></td>
</tr>
<tr>
<td>Deprivation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J.M.</td>
<td>26/M</td>
<td>OD</td>
<td>20/20</td>
<td>59.4 ± 1.34</td>
<td>-6.00-2.25 × 015</td>
<td>Unsteady central</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/155</td>
<td>48.4 ± 3.25</td>
<td>-10.00-1.25 × 125</td>
<td></td>
</tr>
<tr>
<td>C.T.</td>
<td>13/M</td>
<td>OD</td>
<td>20/3488</td>
<td>36.5 ± 1.34</td>
<td>+10.50-1.50 × 180</td>
<td>Temporal fixation, unable to quantify w/haideringer brush, visuscopy, or blind spot plot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OS</td>
<td>20/15</td>
<td>*49.6 ± 0.55</td>
<td>-4.75 D.S.</td>
<td></td>
</tr>
</tbody>
</table>

AE = amblyopic eye; ET = exotropia; XT = exotropia.

*Statistically significant, p < 0.01.

that of the nonamblyopic eye under photopic conditions.13 Although the measurement of CFF represents one limit of temporal resolution, it is in many respects analogous to the measurement of visual acuity in the spatial domain. A more complete description of temporal processing may be obtained by determination of the temporal modulation sensitivity function (de Lange function) over a wide range of temporal frequencies.14-17

Breukink18 measured de Lange functions in a large number of patients with various ocular diseases, including four amblyopic patients, with use of a 2° field. Tyler (personal communication) has reanalyzed Breukink's results and has shown that the temporal visuograms of some amblyopes had substantial losses in overall flicker sensitivity, which may reflect the effects of eccentric fixation. In addition, some of the amblyopes appeared to show notch losses in temporal modulation sensitivity. Spekreijse et al.19 have reported on the temporal modulation sensitivity function of one anisometropic amblyope. When the stimulus field was small (and therefore broadband in its spatial frequency characteristics), the authors found a reduction in the sensitivity of the amblyopic eye to low temporal frequency sinusoidal modulation. The loss of sensitivity, particularly at low temporal frequencies, was greatly exaggerated when the stimuli were counterphase-modulated checkerboards. In addition, there are several other recent reports of abnormal temporal processing of spatial stimuli, studied with both psychophysical20-22 and electrophysiological23 techniques. In general, the abnormalities appear to be more marked for high spatial frequencies modulated at low temporal frequencies.

In this article we report on the temporal characteristics of eight representative strabismic and/or anisometropic amblyopes and two subjects with amblyopia resulting from
stimulus deprivation (caused by unilateral congenital cataract and ptosis) in which the spatial parameters of the stimulus have been minimized. Investigations of spatiotemporal contrast sensitivity in the same observers will be reported separately.24

**Observers.** Eight strabismic and/or anisotropic amblyopes and two stimulus-deprivation amblyopes (congenital unilateral ptosis, J. M.; congenital unilateral cataract, C. T.) participated in these experiments. Throughout all of the experiments, refractive errors were appropriately corrected. All observers had normal fundi and clear media. The relevant visual characteristics for the amblyopic observers are presented in Table I. Three normal observers served as controls.

**Apparatus.** A uniform field was generated on a cathode ray tube (Tektronix 608 high brightness monitor, P45 phosphor) by the method described by Campbell and Green.25 The z-axis of the monitor was modulated to produce a sinusoidal variation in luminance of the entire screen. The modulation depth was controlled via a logarithmic attenuator and could be varied in temporal frequency or modulation depth without changing the mean luminance (32 cd/m²). The screen was masked by a diffusing cone, which provided a surround luminance approximately equal to the average luminance of the monitor and provided a 9° circular test field at the 57 ° cm viewing distance.

**Experiment 1. Uniform field-threshold**

**Methods.** Monocular flicker thresholds were determined by an ascending method of limits for temporal frequencies ranging from 0.5 to 48 Hz. Five thresholds were measured at each temporal frequency, and the order of the temporal frequency presentation was randomized. The observers were familiarized with the task and were given practice trials prior to formal testing. The nonamblyopic and amblyopic eyes were tested during the same session, with the untested eye occluded by a black patch. Five measurements of the CFF for each eye at the maximum contrast (42%) were also determined by a descending method of adjustment. Natural pupils and accommodation were used except where indicated. Viewing distance was maintained by a headrest, and the observer was directed to fixate a small square placed in the center of the stimulus field during the threshold measurements.

**Results.** The temporal modulation sensitivity functions for the nonamblyopic and amblyopic eyes of four amblyopic observers are shown in Fig. 1, A, plotted on log-log coordinates. The data for both the nonamblyopic and amblyopic eyes were characteristic, showing a peak temporal sensitivity between about 7 and 15 Hz and a reduced sensitivity for frequencies above and below this peak. In most cases the peak and the shapes of the functions were similar for the two eyes,26 27 about half the amblyopic observers did show differences between the two eyes.

![Image](https://example.com/image.png)
the averaged standard deviation for each observer; points falling outside this range reflect a significant difference in flicker sensitivity between the two eyes. Inspection of these graphs reveals that the sensitivity of the amblyopic eye of each of the three anisometropic observers (D. B., B. J., and S. K.) and of the strabismic/anisometropic amblyope (L. H.) is reduced compared with that of the nonamblyopic eye, particularly at the low temporal modulation frequencies. For several of these observers (D. B., B. J., and L. H.) the losses in sensitivity may be considered notch losses similar to those seen in the data of Breukink. However, strabismic amblyopes R. C. and C. W. showed little difference between the two eyes, whereas the remaining two observers showed an increase in sensitivity of the amblyopic eye over part (B. W.) or all (J. V.) of the frequency range. There does not appear to be any relationship between the visual acuity in the amblyopic eye and the difference in the temporal modulation sensitivity between the two eyes. Substantial differences in flicker sensitivity can occur with little (B. J.) or moderate (L. H.) reduction in visual acuity, but only small differences may be present in other amblyopes with moderate acuity losses (R. C. and J. V.).

Several reports suggest that some of the deficits observed in humans with stimulus deprivation amblyopia may be different from those present in strabismic and/or anisometropic amblyopia. Although the results of J. M. (amblyopia caused by congenital unilateral ptosis) are similar to those obtained for several strabismic and anisometropic amblyopes, the data of observer C. T. (amblyopia caused by congenital unilateral cataract) show very marked losses in temporal modulation sensitivity (a factor of 2.5 to more than 4) over the entire range of temporal frequencies, with the losses actually increasing at high temporal frequencies.

As shown in Fig. 1, differences in the response between the amblyopic and nonamblyopic eyes to temporal modulation are generally more marked at low temporal frequencies. To examine the responses at high temporal frequencies, the CFF measured for the amblyopic and nonamblyopic eyes were compared by a two-sample t test modified to assume heterogeneity of variance. The means and standard deviations for the CFFs for all observers are shown in Table I.

Four of the eight strabismic and/or anisometropic amblyopes and one stimulus-deprivation amblyope showed significant reductions in CFF. Interestingly, amblyopes with moderate visual acuity deficits showed no significant differences, whereas the amblyopes with the best visual acuity (B. J., B. W., D. B., and S. K.) showed a statistically significant difference in CFF when tested at an average luminance of 32 cd/m². These CFF results were also confirmed by extrapolation of the temporal modulation sensitivity function to 100% modulation. It should be noted that the largest reduction in CFF among these strabismic and/or anisometropic amblyopes was on the order of 10%. For some amblyopes these small reductions in CFF are in agreement with earlier reports. By comparison, losses of temporal sensitivity, when considered in the contrast domain for these same observers, may be greater than a factor of 2 (0.3 log units), particularly at low temporal frequencies. The data of C. T. (amblyopia caused by stimulus deprivation) showed greater losses, with about a 25% reduction in CFF, and marked losses (greater than 0.4 to 0.5 log units) in flicker sensitivity over most of the range. These results show that losses to temporal modulation sensitivity, when spatial aspects of the stimulus are minimized by the use of a large field, are not a consistent feature of amblyopia caused by strabismus and/or anisometropia and do not appear to be related in any direct way to the losses in visual acuity.

Both normal and abnormal pupil sizes and responses have been reported in amblyopic patients. To investigate the effect of possible pupil abnormalities on the temporal modulation function, the effect of a fixed dilated pupil (7 mm) was evaluated for one amblyope (L. H.). The logarithm of the ratio of the sensitivities of the two eyes for this observer is shown in Fig. 1, B, as the filled triangles. Comparing these ratios with those
Fig. 1. A, Temporal modulation sensitivity functions for three strabismic and/or anisometropic amblyopes and one stimulus-deprivation amblyope, measured with a 9° field at 32 cd/m² and plotted on log-log coordinates. Open symbols, Sensitivity of the nonamblyopic eye; filled symbols, sensitivity of the amblyopic eye (1/threshold contrast). The standard errors of the mean were less than the size of the symbols. The function plotted with diamonds for observer C. T. was obtained at a mean luminance of 0.32 cd/m². Triangles, Measured CFF at 42% contrast (presented in Table I with statistical analysis). B, Logarithm of the ratio of sensitivity (nonamblyopic eye to amblyopic eye) as a function of temporal frequency for a 9° field at 32 cd/m² (filled circles), a 2.5° field at 32 cd/m² (open squares), a 9° field at 0.32 cd/m² (filled diamonds), and a 9° field at 32 cd/m² with dilated pupil (filled triangles). Error bars represent two times the averaged standard deviation. Those to the left are for the 9° (32 cd/m²) condition. The error bars for the other conditions are shown on the appropriate symbols. Inset, Representative eye movement traces for nonamblyopic (NAE) and amblyopic (AE) eyes; see text for details.

obtained with natural pupils, the same pattern of response is present. In addition, little difference was seen in the low-frequency portion of the modulation function of a normal observer when tested with a fixed dilated pupil. This is in agreement with the results of Kelly,¹⁷ showing that the low-frequency response is not dependent on the retinal illumination when the response is expressed as sensitivity. Based on the results of this con-
Fig. 2. Suprathreshold isotemporal sensitivity functions representing equal apparent contrast by magnitude estimation for the nonamblyopic (NAE) and amblyopic (AE) eye of a strabismic/anisometropic amblyope with log of the apparent normalized contrast as the parameter (filled circles, −0.4; open circles, −0.8; filled squares, −1.0; filled triangles, −1.2; open triangles, −1.6; open diamonds, threshold). Lower inset, Illustration of how these functions were derived via linear regression of the log of the normalized apparent contrast at different physical contrasts for each temporal frequency. Error bars represent the standard error of the mean for the normalized apparent contrast judgments. Upper inset, Log ratio of the nonamblyopic to amblyopic eye for the threshold condition (open diamonds) and for the largest apparent contrast (filled circles). See text for additional details.

CONTROL STUDY AND THOSE OBTAINED BY KELLY, IT IS DOUBTFUL THAT THE DIFFERENCES OBSERVED IN TEMPORAL MODULATION SENSITIVITY CAN BE ATTRIBUTED TO AN UNDETECTED DIFFERENCE IN PUPIL SIZE OR PUPIL RESPONSES IN THE STRABISMIC AND/OR ANISOMETROTIC AMBLYOPEs.*

ANOMALOUS EYE MOVEMENTS HAVE ALSO BEEN REPORTED IN AMBLYOPEs, AND THEREFORE EYE MOVEMENTS WERE MONITORED WITH AN INFRARED EYE MOVEMENT MONITOR (MODEL 200; G. W. APPLIED SCIENCE LABORATORIES) IN ONE SUBJECT (B. J.) WHO SHOWED LARGE DIFFERENCES IN THE TEMPORAL MODULATION SENSITIVITY OF THE TWO EYES. REPRESENTATIVE TRACES FOR THE NONAMBLYOPIC AND AMBLYOPIC EYES ARE SHOWN IN THEInset in Fig. 1, B. Although small differences are present in the two records, they cannot account for the large difference in the sensitivity of the amblyopic eye with a 9° field, and no bias or difference in drift rate was observed in the records of either eye.

IT IS POSSIBLE THAT THE LARGE TEST FIELD MAY HAVE MASKED DIFFERENCES IN FLICKER SENSITIVITY BETWEEN THE TWO EYES, SINCE THE DEFICITS IN AMBLYOPEA HAVE BEEN REPORTED TO BE CONFINED TO CENTRAL VISION. Therefore flicker sensitivity was measured in five of the eight strabismic and/or anisometropic amblyopes with a 2.5° test field. The results of one of these observers (D. B.) are displayed in Fig. 1, B, as the open squares. This observer, as well as the other amblyopic observers tested, showed results similar to those obtained with the large (9°) test field.

THE LOSS OF SPATIAL RESOLUTION IN AMBLYOPEA IS REPORTED TO BE LUMINANCE DEPENDENT. TO DETERMINE WHETHER THE DIFFERENCES IN THE TEMPORAL MODULATION SENSITIVITY FUNCTIONS BETWEEN THE NONAMBLYOPIC AND AMBLYOPIC EYES WERE ALSO LUMINANCE DEPENDENT, THE SENSITIVITY AS A FUNCTION OF TEMPORAL FREQUENCY WAS MEASURED AT 0.32 cd/m² with a 9° field.
The temporal modulation sensitivity function measured with an average luminance of 0.32 cd/m² is shown for stimulus-deprivation amblyope C. T. in Fig. 1, A. The logarithm of the ratio of sensitivity (nonamblyopic eye/amblyopic eye) for this reduced luminance condition is shown in Fig. 1, B (filled diamonds), for C. T. and for four strabismic and/or anisometropic amblyopes (B. J., S. K., R. C, and J. V.). It appears that there is a substantial normalization of flicker sensitivity for anisometropic amblyopes B. J. and S. K. under the low-luminance condition. It is also interesting that of those strabismic/anisometropic observers who showed a statistically significant difference in measured CFF at a mean luminance of 32 cd/m², none showed a significant difference when tested at the lower luminance.

In contrast to the results of the strabismic and/or anisometropic amblyopes, the data for C. T. showed even larger losses of temporal modulation sensitivity under conditions of reduced luminance, and the CFF of his amblyopic eye was significantly reduced (p < 0.01). This result is in part attributable to differences in pupil size. Under photopic conditions this observer's pupils were approximately equal in area; however, under reduced illumination or pharmacologic mydriasis, the pupil of his amblyopic eye failed to dilate because of anterior synechia. Thus, under conditions of reduced illumination or pharmacologic mydriasis, there was a significant difference in pupil area. In an attempt to equate pupil area in the two eyes under the reduced-luminance condition, an artificial pupil was placed before the nonamblyopic eye. Under this condition, the difference between the two eyes (shown by the open triangles in Fig. 1, B) was similar to that observed at 32 cd/m² at the low temporal frequencies. This result is somewhat surprising, since the temporal modulation sensitivity at low frequencies is considered to be largely independent of mean luminance over a wide range of luminance levels. Nonetheless, the results for this severe stimulus-deprivation amblyope show large reductions in flicker sensitivity for uniform field flicker at both luminance levels.

Experiment 2. Uniform field-suprathreshold

Hess and Bradley have shown that the losses of spatial contrast sensitivity, evident at the detection threshold for amblyopic eyes, may be diminished or eliminated at higher contrast levels. To examine the temporal modulation sensitivity at suprathreshold levels, we performed an additional experiment.

Methods. A magnitude estimation paradigm similar to that described by Stevens and Marks was used to determine the temporal modulation sensitivity function to suprathreshold modulation of a 9° homogenous field.

The temporal frequency and contrast level of the stimulus were randomly selected and set by the experimenter and presented to the observer for 2 sec. The observer was instructed to assign a number to the stimulus, which represented the magnitude of the temporal modulation irrespective of the frequency of modulation. If the screen appeared uniform the observer was instructed to assign it a value of zero. Ten to 15 randomly selected stimuli were presented at the beginning of each session to provide the observer with a sampling of the contrast levels likely to be presented.

Monocular judgments were made with both the nonamblyopic and amblyopic eyes over a range of contrast levels for sinusoidal modulation of 0.5 to 48 Hz. Ten estimates of apparent modulation were made with the nonamblyopic and amblyopic eyes at each temporal frequency and contrast level used; one estimate by each eye for each combination of contrast and frequency was completed by the subject in a single session. To avoid scaling differences that might confound comparisons between the suprathreshold temporal modulation sensitivity functions of the nonamblyopic and amblyopic eyes, the observer was instructed to assign the same numbers to the same apparent modulation irrespective of the viewing eye.

Results. Monocular suprathreshold “iso-sensitivity” functions are shown in Fig. 2 for the nonamblyopic and amblyopic eyes of observer L. H. These functions were obtained by plotting the normalized mean apparent contrast as a function of the logarithm of the reciprocal of the contrast at each temporal frequency. The lower inset of Fig. 2 shows the function obtained for the amblyopic eye of L. H. at 6 Hz. The standard error of the mean was less than the size of the symbol...
unless illustrated with error bars. Linear regression was used to determine the best-fit line at each frequency for each eye. Regression coefficients were $-0.96$ or higher. With the equations obtained, isosensitivity functions were derived by calculating the physical contrast necessary to provide a given apparent contrast at each temporal frequency. The functions shown in Fig. 2 are the result of these manipulations, with the different symbols representing equal sensitivity for several apparent contrast levels. It is interesting to note the similarity in the isosensitivity functions for the nonamblyopic and amblyopic eyes at high apparent contrasts. The upper inset in Fig. 2 shows the logarithm of the ratio (nonamblyopic eye/amblyopic eye) at threshold (diamonds replotted from Fig. 1, B) and at the highest apparent contrast level (circles). Little difference is present in the functions of the two eyes at suprathreshold contrast levels.

Discussion

Although losses of sensitivity in the spatial domain characterize all types of amblyopia, only about 50% of the strabismic and/or anisometropic amblyopes in the present study showed losses of temporal modulation sensitivity. When differences between the two eyes were found they were usually more marked at low temporal frequencies and were fairly small in magnitude in comparison with the losses in the spatial domain. The pattern of loss of temporal modulation sensitivity in amblyopia appears to differ from that recently described in glaucoma patients by Tyler, who reported losses for a narrow range of medium temporal frequencies (primarily notch losses). Our results also differ somewhat from those of Breukink, possibly because of his use of a small field and observers with large degrees of eccentric fixation. Since the largest differences occur at low temporal frequencies, where Kelly has shown the response to be independent of retinal illumination and thus pupil size, undetected anisocoria or differences in pupil responses of the amblyopic eye cannot account for the measured differences in observers with strabismic and/or anisometropic amblyopia. The control experiments further suggest that the losses of sensitivity are not the result of pupil differences or anomalous eye movements.

It is interesting that the differences in temporal sensitivity at both high and low frequencies are reduced or eliminated under conditions of low mean luminance and for apparent contrast judgments at suprathreshold levels. Hess et al. and Caloroso and Flom have shown that the spatial resolving capacity of the amblyopic eye also approaches that of the nonamblyopic eye at low luminance levels. In addition, the normalization seen in temporal detection at suprathreshold levels (Fig. 2) may also be found in the spatial domain in some amblyopes.

The largest losses of temporal modulation sensitivity were found in observer C. T., whose amblyopia resulted from stimulus deprivation caused by congenital unilateral cataract. For this observer, substantial losses in temporal modulation sensitivity were found at all temporal frequencies. Thus it appears that in severe amblyopia resulting from stimulus deprivation, the pattern of loss is different from that found in the more commonly occurring strabismic and anisometropic amblyopes. Moreover, the losses were still present under reduced luminance conditions. Recent behavioral studies of monkeys reared with unilateral lid suture suggest that the absolute threshold of the deprived eye is elevated. Since this does not occur in strabismic and/or anisometropic amblyopia, it is likely that different neural losses may occur in amblyopia resulting from different types of early visual deprivation.

Losses of temporal resolution (CFF) in amblyopia of varying etiology are very small when the spatial aspects of the stimulus are minimized. Larger losses of temporal sensitivity in the contrast domain were found to occur primarily at low temporal frequencies in about 50% of the strabismic and anisometropic amblyopes and over a wider range of temporal frequencies in one subject with amblyopia caused by early stimulus deprivation. However, these losses are small in comparison with the losses of spatiotemporal
contrast sensitivity described in the following article. Perhaps this is not surprising in view of the recent report of Regal, showing that in comparison with spatial acuity, CFF is highly developed very early in life.

We wish to thank Ronald S. Harwerth and Earl L. Smith for their helpful discussions and suggestions.

REFERENCES
34. Hess RF, Campbell FW, and Zinnern R: Differ-


