Psychophysical investigations of the temporal modulation sensitivity function in amblyopia: spatiotemporal interactions

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Temporal modulation sensitivity functions were measured in response to counterphase sine-wave gratings of various spatial frequencies in seven strabismic and/or anisometropic amblyopes and in two stimulus-deprivation amblyopes. Both movement/flicker and pattern detection thresholds were determined. Strabismic and/or anisometropic amblyopes showed reduced sensitivity for movement/flicker and pattern detection in the amblyopic eyes, which were dependent on both the spatial and temporal frequencies of the stimulus and the detection criterion. At medium and high spatial frequencies, substantial reductions in movement/flicker detection were present, which were generally more marked for low temporal modulation frequencies. Reductions in pattern sensitivity were greater at the higher spatial frequencies, although some amblyopes showed losses in sensitivity at low spatial frequencies as well. The losses observed in the spatiotemporal transfer function of the amblyopic eyes were greater than those found with unstructured stimuli (uniform field flicker) and were not eliminated under reduced luminance. In subjects with amblyopia caused by stimulus deprivation, losses in spatiotemporal contrast sensitivity were either invariant across temporal frequencies or increased at higher rates of temporal modulations. (INVEST OPHTHALMOL VIS SCI 22:525-534, 1982.)

Key words: amblyopia, spatiotemporal contrast sensitivity function, spatiotemporal surface, temporal modulation, psychophysics

Functional amblyopia resulting from strabismus and/or anisometropia or form deprivation early in life is generally considered to represent a deficit in spatial vision. In the preceding article\(^1\) we reported that when the spatial parameters of the stimulus were minimized, the critical fusion frequency (CFF) of the amblyopic eye was equal to that of the nonamblyopic eye or was only slightly reduced. When temporal resolution was evaluated at other modulation frequencies, however, somewhat larger deficits in temporal contrast sensitivity, particularly at low frequencies, were observed in half of the amblyopes tested. In the present article we have extended the investigation of temporal processing into the spatial domain by presenting the results of investigations of spatiotemporal contrast sensitivity in humans with naturally occurring amblyopia caused by strabismus and/or anisometropia and form deprivation. The results obtained are important in characterizing the performance properties of the visual system of humans with naturally occurring amblyopia of various causes and may also allow comparisons with the results obtained in animal models of amblyopia.

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This investigation was supported by grant ROI EY01728 from the National Eye Institute.
Submitted for publication Jan. 27, 1981.
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0146-0404/82/040525+10$01.00/0 © 1982 Assoc. for Res. in Vis. and Ophthal., Inc.

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Materials and methods

Observers. The same observers described in Table I of the preceding article (with the exception of B. W.) as well as three observers with normal binocular vision participated in these studies.

Procedure. Vertical sinusoidal gratings with a space averaged luminance of 32 cd/m² were generated on the cathode ray tube of a Tektronix 698 monitor (P45 phosphor) by a method similar to that described by Campbell and Green. The circular screen was masked by an equiluminance surround to subtended 9° at the observers' eye, which ensured that at least nine cycles of the grating were present. The contrast of the gratings was reversed sinusoidally by amplitude modulation of the input to the z-axis. At each of several spatial frequencies, temporal modulation sensitivity functions were determined by measurement of contrast thresholds for both the pattern and movement/flicker criteria (as described by Keesey and Kulikowski and Tolhurst). The range of temporal frequencies investigated was 0.5 to 48 Hz. Within a single session, five measurements for each detection threshold (movement/flicker and pattern) were determined at each temporal frequency for both the nonamblyopic and amblyopic eyes at one spatial frequency. Additional procedures were as described in the preceding article.

Results

Strabismic and/or anisometropic amblyopia. Fig. 1 displays the logarithm of the ratio of the threshold (nonamblyopic eye/amblyopic eye) for pattern detection and movement/flicker detection for amblyopic observer J. V. for gratings of 2, 4, and 8 cy/deg.

At low spatial frequencies (e.g., 2 cy/deg or lower) little difference was seen in the flicker detection between the two eyes, but the amblyopic eye was less sensitive to the detection of pattern. Hess et al. have reported a similar selective reduction in pat-
tern sensitivity at low spatial frequencies in an observer with strabismic amblyopia and concluded that the pattern-detecting mechanism was selectively affected. At higher spatial frequencies, a reduction in both the movement/flicker and pattern sensitivity of the ambyopic eye was present and was more marked at the low temporal modulation frequencies. Surprisingly, when an 8 cy/deg grating was counterphase modulated at 0.50 Hz, observer J. V. was unable to detect any movement or flicker when viewing with the ambyopic eye at the highest contrast available (C = 0.42).

The results of each of the strabismic and/or anisometropic amblyopes tested were similar to those of J. V. All showed losses in pattern sensitivity that were more marked at high spatial frequencies, and all showed substantial losses in sensitivity to slow temporal changes (counterphase modulation below 4 Hz), which occurred primarily at high spatial frequencies. These decreases in sensitivity, particularly for the movement/flicker threshold, appeared to show a direct relationship to the loss in visual acuity, with the more severe amblyopes showing greater losses in sensitivity. In addition, these reductions in sensitivity appeared at low as well as high spatial frequencies in the more severe amblyopes. The present study confirms the recent report by Schor and Levi which showed large reductions in the sensitivity of the ambyopic eye to flicker or movement of a 6 cy/deg grating at low rates of counterphase alteration. They have also noted a relationship between the visual acuity in the ambyopic eye and the decrease in sensitivity to movement/flicker detection similar to that we report here. It is interesting that three anisometropic amblyopes without strabismus showed reductions in sensitivity at all temporal frequencies, whereas three of the strabismic amblyopes showed larger losses at low temporal frequencies than those shown at high frequencies. However, this distinction is not clear-cut, since observer C. W. (strabismic without anisometropia) showed reduced sensitivity at all temporal frequencies when the spatial frequency was high (see Fig. 2).

The sensitivity of the visual system for various spatial and temporal frequencies can be summarized by constructing a spatiotemporal threshold surface. Several investigators have plotted such a function for observers with normal vision. Fig. 2, A, shows the spatiotemporal contrast surface for each eye of strabismic ambyope C. W. The points represent the lowest detection threshold, movement/flicker or pattern, whichever was detected first.

The results of C. W. were similar to those described for J. V. and the other strabismic/anisometropic amblyopes at low temporal and high spatial frequencies. Little change in sensitivity was apparent at any given temporal frequency as spatial frequency was increased from 1 to 4 cy/deg in the nonamblyopic eye or from 1 to 2 cy/deg in the ambyopic eye, and little difference in sensitivity was present between the nonamblyopic and ambyopic eyes at 1 and 2 cy/deg. Although small differences in sensitivity were apparent at 4 cy/deg, the greatest difference occurred at 8 cy/deg, where the sensitivity of the ambyopic eye was substantially reduced at all temporal frequencies. Because the spatiotemporal surface shown in Fig. 2, A, was constructed from the lowest detection threshold regardless of the criterion used (pattern or movement/flicker), deficits that may differentially affect one of the detection thresholds might not be apparent in the surfaces, depending on the region where the deficit occurred. To display the differences in pattern and movement/flicker detection present in C. W. as a function of both temporal and spatial frequency, two additional surfaces have been constructed. Fig. 2, B, shows the logarithm of the ratio of the nonamblyopic eye to the ambyopic eye as a function of temporal and spatial frequency for the detection of pattern, and Fig. 2, C, displays a similar surface for movement/flicker detection. At low spatial frequencies (1 and 2 cy/deg) there was little difference in the sensitivity values of the nonamblyopic and ambyopic eyes for pattern detection, with most points
Fig. 2. A, Spatiotemporal detection surface of the nonamblyopic eye (NAE) (left) and amblyopic eye (AE) (right) for strabismic amblyope C. W. Points represent the detection threshold with the most sensitive measure, movement/flicker or pattern being plotted. B, Logarithm of the ratio of sensitivity (nonamblyopic eye/amblyopic eye) for C. W. for the detection of pattern as a function of spatial and temporal frequency. C, As in B for the detection of movement/flicker. Shaded area, Lower limit of sensitivity loss in regions where no threshold could be determined at 42% contrast. D, Schematic representation of the loss in sensitivity as a function of spatial and temporal frequency for various amblyopes.
on the surface falling close to zero. However, as spatial frequency was increased, the sensitivity of the amblyopic eye decreased and the surface sloped upward.

The relative sensitivity values of the non-amblyopic and amblyopic eyes for the detection of movement/flicker (Fig. 2, C) were more irregular. As in the detection of pattern, little difference was seen between the values for the two eyes at low spatial frequencies (1 cy/deg). However, as spatial frequency increased, the sensitivity of the amblyopic eye decreased, and the difference was larger than that observed for pattern detection, particularly at the low and middle temporal frequencies. At 8 cy/deg, movement/flicker could not be detected at the low temporal modulation frequencies, and the sensitivity was greatly reduced at the four midtemporal frequencies where movement/flicker could be detected by the amblyopic eye. The shaded area enclosed by the dashed lines represents the lower limit of the sensitivity loss in those regions where no threshold could be determined at 42% contrast. These two additional surfaces show the large deficit in the detection of movement/flicker that was also present for J. V. and other amblyopic observers tested and that was not apparent in the spatiotemporal surface in which only the first detection threshold is displayed.

Magnitude estimates of contrast sensitivity.

At low spatial frequencies some amblyopes showed selective losses in pattern thresholds (e.g., J. V. in Fig. 1 and L. H. in Fig. 3, C), but at medium-to-high spatial frequencies and low temporal frequencies there may be greater losses in sensitivity to the temporal attributes of the stimulus (movement/flicker). Schor and Levi have suggested that the reduction in sensitivity to slow movement/flicker of a medium-to-high spatial frequency counterphase grating may result from inhibition between mechanisms that are sensitive to opposite directions of motion. Direction-selective mechanisms have been shown to saturate in their response to contrast at very low contrast levels, whereas nonselective channels combine to operate at higher contrast levels. Therefore, if the reduction in movement/flicker sensitivity of the amblyopic eye results from selective abnormalities in direction-specific mechanisms, no loss in suprathreshold contrast sensitivity would be expected. To determine whether the reduced movement/flicker sensitivity at threshold influenced the apparent contrast of suprathreshold spatiotemporal gratings, we conducted an additional experiment at suprathreshold levels with a magnitude estimation procedure. The experimental details have been described in the preceding article. Fig. 3 shows the suprathreshold "isosensitivity" functions for the nonamblyopic and amblyopic eyes of observer L. H. for a 4 cy/deg grating modulated at various temporal frequencies. The logarithm of the ratio (nonamblyopic eye/amblyopic eye) at several suprathreshold contrast levels as well as at the pattern threshold and the movement/flicker threshold are shown in Fig. 3, C. It is clear from these results that the substantial reduction in sensitivity to the temporal aspects of the stimulus at low temporal frequencies, evident at threshold, do not influence the apparent contrast of the 4 cy/degree grating at suprathreshold levels. This result further suggests that the movement/flicker-detecting mechanism is not involved in the coding of suprathreshold contrast.

Effect of mean luminance.

The results of the present experiments differ from those of the preceding investigation in showing much larger losses in spatiotemporal contrast thresholds than were found with a uniform flickering field. The results obtained with spatiotemporal grating patterns also differ in their luminance dependence. The logarithm of the ratio (nonamblyopic eye/amblyopic eye) for the reduced luminance condition (0.32 cd/m²) at 4 cy/deg is shown in Fig. 1 for both pattern and movement/flicker detection. Comparing these results to those obtained at 32 cd/m², it is clear that there is no normalization of function under reduced illumination for spatiotemporal gratings with a spatial frequency of 4 cy/deg. Similar results were also obtained for observers L. H. and C. W.

Amblyopia caused by stimulus deprivation.

The data of J. M. (moderate ambly-
opia caused by congenital unilateral ptosis) showed a uniform reduction in sensitivity to both movement/flicker and pattern at all temporal frequencies. This was similar to the results of several strabismic and/or anisotropic amblyopes and is in agreement with the findings of France et al.\textsuperscript{14} Fig. 4 shows data for C. T. (amblyopia caused by congenital cataract) for a 1 cy/deg grating at various counterphase frequencies. The results for this observer are quite surprising in that he was unable to discern flicker or apparent movement with his amblyopic eye at any temporal frequency. In addition, his sensitivity for detecting pattern was reduced by a factor of about 1.5 log units for temporal frequencies between 0.5 and about 6 Hz. At higher temporal frequencies we were unable to measure even pattern thresholds for the amblyopic eye. This result was rather surprising, since there are two reports suggesting that severe amblyopia resulting from stimulus deprivation may result in a complete loss of pattern perception, with only flicker perception remaining.\textsuperscript{14, 15} To minimize possible criteria difficulties, we also measured C. T.'s spatial contrast sensitivity with two different temporal presentations: (1) a Gaussian function with a time constant of 0.25 seconds (S-modulation) and (2) one cycle of an 8 Hz square-wave contrast reversal (T-modulation). The Gaussian modulation has been shown to elicit the properties

Fig. 3. "Isosensitivity" curves plotted as a function of counterphase modulation frequency in response to a 4 cy/deg sine-wave grating for the nonamblyopic eye (A) and amblyopic eye (B) of observer L. H. The different symbols represent the logarithm of different apparent contrast levels that have been normalized (open circles, \(-0.4\); filled squares, \(-0.6\); open triangles, \(-0.8\); open diamond, \(-1.0\)). The log of the ratio (nonamblyopic eye to amblyopic eye) is plotted in C as a function of temporal frequency for the highest apparent contrast (open circles, 0.4), and a low apparent contrast (open diamonds, 1.0). Also shown is the ratio obtained at threshold for movement/flicker detection (filled triangles) and pattern detection (filled circles).
of relatively sustained (pattern-sensitive) mechanisms, and the 8 Hz square-wave preferentially stimulates transient (movement/flicker-sensitive) mechanisms. For both forms of modulation the contrast sensitivity of the amblyopic eye was extremely reduced. However, the losses in sensitivity to T-modulation were greater, confirming the results presented in Fig. 4. The present result is in contrast to that of the recent report by Hirsch et al., suggesting that strabismic and anisometropic amblyopes show greater losses in sensitivity to S- than to T-modulation.

Summary and discussion

The present results show that amblyopia may be characterized not only by losses in spatial contrast sensitivity but also by losses in sensitivity to temporal parameters of spatial stimuli. The results for strabismic and anisometropic amblyopia may be summarized as follows:

(1) At low spatial frequencies, losses may occur selectively in pattern detection, whereas movement/flicker detection is essentially normal.

(2) At medium and high spatial frequencies there are marked reductions in sensitivity for both pattern and movement/flicker detection. For some amblyopes these losses are most marked at low temporal frequencies, with smaller or no loss of sensitivity at high temporal frequencies. This pattern was noted in most but not all the amblyopic observers with strabismus. Some amblyopes tended to show reductions in sensitivity at all temporal frequencies. Three anisometropic amblyopes and one strabismic amblyope demonstrated this pattern of loss.

(3) For all observers, very pronounced reductions in sensitivity to movement/flicker at low temporal counterphase modulation frequencies and high spatial frequencies were found. This loss of sensitivity to movement/flicker at threshold does not influence suprathreshold contrast perception. It is also interesting to note that the loss of sensitivity to movement/flicker at low temporal and high spatial frequencies is much greater than that found at the detection threshold (Fig. 3) under these stimulus conditions. In normal subjects detection appears to be mediated by non-direction-selective (pattern) mechanisms, and higher contrast is required to detect the direction of a drifting grating or the flicker/pattern of a counterphase grating.

(4) The reduction in spatiotemporal contrast sensitivity for medium spatial frequencies is found under both high and low luminance conditions (Fig. 1, filled symbols).

(5) One observer with moderate amblyopia caused by stimulus deprivation showed a uniform reduction in pattern and movement/flicker sensitivity across temporal frequencies.
cies; however, observer C. T. with severe amblyopia caused by stimulus deprivation showed marked losses in pattern sensitivity and an absence of sensitivity to movement/flicker. The loss in pattern sensitivity was greatest at high temporal frequencies. For this observer, greater losses were also found in detection of gratings modulated with T-modulation than those with S-modulation. For the stimulus-deprivation amblyopes, the losses in sensitivity are either equal across temporal frequencies (J. M.) or increase at higher temporal frequencies (C. T.). The results of J. M., a moderate amblyope, are similar to those found in the three anisometropic amblyopes without strabismus and in C. W., who was strabismic without anisometropia. The results of C. T., a severe stimulus deprivation amblyope, were different from any of the other amblyopes tested.

(6) In contrast to the spatiotemporal losses, when the stimulus was a homogenous field, only about half of the strabismic and anisometropic amblyopes showed reductions in temporal modulation sensitivity. These losses were (1) generally small in comparison with the losses described in the spatial domain, (2) most marked at low frequencies, and (3) not evident at suprathreshold conditions or under low luminance levels. Only observer C. T. (severe amblyopia caused by stimulus deprivation) showed marked losses in sensitivity at all temporal frequencies and under conditions of reduced illumination.

These results are further summarized in a very schematic form in Fig. 2, D, for the various types of amblyopia studied.

Relevance to animal models. Ikeda and Wright measured the temporal resolution of cells in the lateral geniculate nucleus (LGN) of kittens with a convergent squint. Their results showed a small but statistically significant reduction in the CFF of the "transient" cells receiving input from the area centralis of the squinting eye; however, the difference was small in comparison with the loss of spatial resolution of the sustained neurons. These results are qualitatively similar to the small losses in CFF found in some humans with strabismic and/or anisometric amblyopia.

Less complete information is available on the spatiotemporal resolution in cats or monkeys reared with strabismus or anisometropia. Therefore an adequate explanation of the large losses of movement/flicker sensitivity at medium-to-high spatial frequencies at low temporal frequency counterphase modulation noted in humans in the present study requires additional physiological investigation before parallels may become apparent. Schor and Levi ascribed this loss of sensitivity to inhibition between mechanisms sensitive to opposite directions of motion.

There are several recent reports of behavioral and electrophysiological studies of spatiotemporal resolution in animals reared with form deprivation caused by monocular or binocular lid suture. Loop et al. reported that binocularly deprived cats showed a reduced CFF at both high and low levels of retinal illuminance. This result is similar to the CFF deficit shown by observer C. T. (amblyopia caused by stimulus deprivation) and was interpreted by Loop et al. to reflect the selective loss of Y-cells found in the LGN of cats reared with stimulus deprivation. The spatial and temporal contrast sensitivity of neurons in the LGN of cats reared with monocular lid suture has been recently reported by Lehmkuhle et al. Their results suggest that X-cells in the deprived laminae exhibited a reduction in sensitivity to higher spatial frequencies, whereas the few Y-cells studied showed normal spatial sensitivity. Neither X- nor Y-cells showed abnormalities in temporal contrast sensitivity (measured for the optimal spatial frequency of each cell). Unfortunately no data are reported regarding the temporal resolution for nonoptimal spatial frequencies (i.e., those at which the effects of the deprivation were most marked). Behaviorally, the contrast sensitivity of the deprived eyes was reduced by about 1.5 log units for all spatial and temporal frequencies tested. The results obtained in these investigations are consistent with the findings of previous studies of severely amblyopic hu-
mans with amblyopia caused by stimulus deprivation\textsuperscript{14, 15} and with the data of C. T. in the present study.

The results of the present experiments suggest rather different patterns of losses in spatiotemporal contrast sensitivity in subjects with amblyopia of different causes. These results, in conjunction with previous reports of prolonged integration time\textsuperscript{25, 26} and reaction time\textsuperscript{27} in the ambyopic eye when tested with gratings of high spatial frequencies, show abnormalities in temporal processing of spatial stimuli and suggest that the type of deprivation (e.g., strabismus and/or anisometropia or stimulus deprivation) may, as has been shown in animals, profoundly influence the pattern of loss.

We thank Ronald S. Harwerth and Earl L. Smith for their review and discussion of the manuscript. We also thank Ronald S. Harwerth for the use of his laboratory and apparatus used in the S- and T-modulation experiment.

Note added in proof

Rentschler, Hiltz, and Brettle (Invest Ophthalmol Vis Sci 20:695, 1981) have also reported reduced sensitivity to flicker at high spatial frequencies in amblyopic observers. They have interpreted this to show abnormal sensitivity to changes in spatial phase.

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