Normal and amblyopic contrast sensitivity functions in central and peripheral retinas

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Contrast sensitivity functions (CSF's) for temporally modulated sine wave gratings were established at a variety of retinal eccentricities in three esotropic amblyopes with acuities in their amblyopic eyes of 20/50, 20/100, and 20/300. CSF's were shown to vary with eccentricity and the degree of amblyopia. In the 20/50 amblyope, reduced CSF's were confined to the higher spatial frequencies and to the central 5° of the retina. Given greater acuity deficits (e.g., 20/100 and 20/300), CSF's were depressed over the entire spatial frequency range tested, with the effects intruding farther into the peripheral retina than for the 20/50 amblyope. In addition, the detection of the temporal as well as the spatial modulation was depressed in the CSF's of the observers with severe amblyopia.

Key words: contrast sensitivity function, strabismus, esotropia, amblyopia, receptive field, sustained and transient neuron, pattern and flicker detection

The most frequent cause of functional impairment of vision is the condition of amblyopia. It is usually associated with uncorrected anisometropia or unilateral strabismus of early onset. Amblyopia is three to four times more frequent with esotropia than exotropia in strabismic cases. Since accommodation and fixation for the convergent eye, in an esotropic visual system, are determined by the normal eye, the convergent eye's fovea is habitually exposed to defocused images of low contrast and blurred detail. The fovea of the convergent eye therefore receives images whose quality is similar to the quality of images received by the normal peripheral retina for objects lying at different distances from the plane of fixation.

Ikeda and Wright report that the central 5° of the cat retina, with its abundance of sustained cells, is particularly sensitive to refractive errors. Recently Ikeda and Wright examined the effects of induced esotropia in kittens on the responses of sustained and transient cells for both central and peripheral projections to the lateral geniculate nucleus. Briefly, sustained cells, driven by the convergent eye, displayed lower spatial frequency cut-offs than the sustained cells innervated by the normal eye. The sustained cell population displaying these relatively reduced cut-offs were confined to the central 5° of the retina. Interestingly, the transient cells for both the convergent and the normal eyes exhibited similar spatial frequency cut-offs regardless of retinal location. It appears, then, that the adverse effects resulting from esotropia might be restricted to the central retinal region and confined to the sustained cell system.

Sustained cells and transient cells may underly the detection of the spatial and temporal aspects, respectively, of temporally modulated grating targets. The contrast sensitivity function (CSF) therefore would allow for the psychophysical examination of...
Normal and amblyopic CSF's

spatiotemporal interactions in an amblyopic visual system over a wide range of spatial frequencies.

It has been demonstrated that amblyopia involves more than a simple reduction in the ability to detect higher spatial frequencies. Amblyopic CSF's, obtained foveally, were reduced in sensitivity at the low and medium spatial frequencies, as well as the high.

The present study examined CSF's for a variety of retinal positions in esotropic amblyopes. On the basis of the findings of Ikeda and Wright it was expected that any amblyopic CSF reductions found in the fovea would eventually disappear in the peripheral retina. Furthermore, it was expected that the detection of the temporal aspects of the grating targets would be relatively unaffected by this type of amblyopia.

Method

Observers. Three adult esotropic amblyopes, all treated after the age of 6 years, were used as observers in this experiment. Visual acuities in their amblyopic eyes were 20/50, 20/100, and 20/300. All three observers demonstrated unsteady
Fig. 2. Contrast sensitivity is plotted as a function of spatial frequency for the nonamblyopic and amblyopic eyes of Observer J. A. (O.D. 20/20, O.S. 20/100). CSF's are shown for the fovea and for 2°, 5°, and 10° in the temporal retina.

but central fixation with their amblyopic eyes. The observers were ophthalmically examined, and each wore his corrective lenses throughout the entire period of testing.

Apparatus. Sine wave gratings were produced on the face of a Tektronix oscilloscope (Model 5103N; Tektronix, Inc., Beaverton, Ore.). The gratings were square-wave modulated at a temporal frequency of 5 Hz.

Observers viewed the gratings on the oscilloscope screen which was masked down to 3°. A large white matte background (20° by 20°) surrounded this display. The screen was 117 cm from the observer. The background was illuminated with a projector whose light was adjusted with neutral-density filters and Wratten filters, to match the color and average luminance (10 cd/m²) of the oscilloscope display. Small (10°) black dots were placed on the background at various distances from the target center along the horizontal meridian as fixation points.

Procedure. Observers were given a number of pretraining sessions to provide experience in determining thresholds for flicker and pattern detection.

At the beginning of each testing session, observers light-adapted to the background and target luminance for 5 min. After the adaptation period observers made threshold adjustments for a number of spatial frequencies. The spatial frequencies chosen were 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 7.5, 10.0, 12.5, and 15.0 c/deg. The observer made four
Fig. 3. Contrast sensitivity is plotted as a function of spatial frequency for the nonamblyopic and amblyopic eyes of Observer P. P. (O.D. 20/20, O.S. 20/300). CSF’s are shown for the fovea and for 2°, 5°, and 10° in the temporal retina.

Threshold adjustments for flicker and pattern detection at each of the 10 spatial frequencies. Four retinal positions were used for testing: 0° (central fixation), 2°, 5°, and 10° temporal retina. A single session consisted of four contrast settings for each of the 10 spatial frequencies at one retinal site. There were two sessions for each of the four retinal positions.

The mean of the eight contrast threshold determinations were used for the data points of the contrast sensitivity functions. Contrast is defined as $L_{\text{max}} - L_{\text{min}} / L_{\text{max}} + L_{\text{min}}$ where $L_{\text{max}}$ and $L_{\text{min}}$ are the maximum and minimum luminances of the light and dark bars, respectively. A standard error of less than 5% was yielded for each data point.

It has recently been shown that in a strabismic amblyope, the nonamblyopic eye’s CSF is essentially normal in all respects. Therefore each observer served as his own control, in that comparisons were made between the amblyopic and nonamblyopic eyes.

Results

Fig. 1 illustrates the CSF’s for Observer R. R. (O.D. 20/20, O.S. 20/50). The greatest amblyopic deficits noticed were in the form of a reduced pattern sensitivity for the higher
spatial frequencies in the fovea and at 2° in the periphery. These differences between the amblyopic and the nonamblyopic functions were not as pronounced at 2° when compared to the foveal functions. The contrast functions for the two eyes were somewhat similar at 5° and 10°.

The foveal functions showed all the characteristics of normal CSF's; that is, there was a peak sensitivity around 3 cy/deg with the typical low and high frequency attenuations. Sensitivity to flicker was greater than to pattern at the low spatial frequencies with a crossover somewhere around 3 to 4 cy/deg.

The CSF changes which occur with eccentricity may be summarized as follows: (1) a depression in function sensitivity for both pattern and flicker at the middle to high spatial frequencies, (2) a reduction in the cut-off frequency, and (3) a shift to the lower spatial frequencies for the peak sensitivity.

Fig. 2 displays the CSF's for Observer J. A. (O.D. 20/20, O.S. 20/100). When this figure is compared with Fig. 1, it can easily
be seen that as amblyopic acuity diminished, the differences between the amblyopic and nonamblyopic functions became more extensive. The amblyopic deficits were now apparent at the low and middle spatial frequencies as well as at the high. The amblyopic foveal functions of this observer displayed a reduced sensitivity for the detection of the temporal aspects of the stimulus. These temporal differences all but disappeared at 2° in the periphery. The amblyopic pattern deficits, on the other hand, were still noticeable at 10° from the fovea. However, these pattern detection differences give indication of narrowing with eccentricity.

Fig. 3 illustrates the CSF's for Observer P. P. (O.D. 20/20, O.S. 20/300). The amblyopic functions of this observer display dramatic deficits for both the detection of pattern and flicker. In the fovea and at 2° in the periphery there was no apparent low frequency attenuation (given the spatial frequencies tested) for the amblyopic eye. The amblyopic eye displayed an increase in sensitivity at 5° and 10° from the fovea. At these eccentric sites there was a relative increase in amblyopic acuity, with very apparent low frequency attenuations. Accompanying these eccentric changes was a concomitant increase in overall amblyopic function sensitivity. The deficits noticed in detecting flicker dropped off somewhere between 5° and 10°. Yet at 10° the amblyopic eye still demonstrated a relatively reduced acuity limit.

There appeared to be an eccentric area in Observer P. P.'s temporal retina which corresponds to the locus of maximum acuity. This is in direct agreement with clinical reports by Burian and von Noorden. The nasal test letters fixated by the amblyopic eye appear brighter and more clearly defined on the side corresponding to the strabismic deviation. This implies that the temporal retina, not the nasally fixated retina in esotropes, is the site of maximum visual acuity. To test this clinical observation empirically, CSF's were obtained from Observer P. P.'s nasal and temporal retina at 2°, 5°, and 10° from the fovea.

Discussion

Amblyopia has been specified as a unilateral dullness of vision characterized by a reduction in visual acuity. This classic definition of amblyopia implies that the higher spatial frequencies in the CSF would be most affected by this anomaly. The CSF results obtained from the 20/50 amblyope support this acuity interpretation of amblyopia. Relative reductions in the ability to detect the higher spatial frequencies were confined to the central 5° of the retina for this degree of amblyopia. Since sustained neurons may underlie the detection of pattern (particularly detailed pattern information) and the density of this neuron type is greatest in the central retinal region, the CSF results obtained might be explained by a selective neuronal "deficiency" of the sustained type system.

It has been suggested that transient neurons may underlie the detection of pattern at the very low spatial frequencies and with temporal modulation of the stimulus. With the observed depression in sensitivity at the low and medium spatial frequencies for the 20/100 and 20/300 amblyopes, it would appear that the transient neurons, with their relatively larger receptive field dimensions, are also affected by the "early" esotropic refractive errors. It would logically follow from this argument that if "larger" receptive fields are affected by amblyopia, the ability to de-
tect the temporal aspects of the stimulus, in this study, would also be reduced. Since the amblyopic detection of pattern was relatively reduced as far out as 10° in the periphery for these two observers and the amblyopic flicker-detection reductions had disappeared at this eccentric location, it might also be suggested that strabismic amblyopia, regardless of degree, reflects a greater sustained neuron deficiency than transient. This is in direct agreement with the electrophysiological results found by Ikeda and Wright.5

It has been noted that with severe amblyopia there is an eccentric retinal region which corresponds to the locus of maximum visual acuity.11 Frequently, the esotropic amblyopic eye fixates with a retinal site other than the foveal center.1 This eccentric fixation response, if present during the human “susceptible period,” could lead to neuronal modifications resulting in the reduced sensitivity for the central CSF’s noticed for the 20/100 and 20/300 amblyopes in the present study.

Typically, esotropes display a nasal fixation and exotropes a temporal fixation. Clinical observations12 and Fig. 4 of this investigation point to the temporal retina as the site of maximum visual acuity in esotropes. To avoid confusion and diplopia, the deviated eye’s fovea and eccentric area on which the object of attention is focused must be excluded from vision. By some form of binocular perimetry (e.g., haploscopic device), it can be shown that in the deviated eye there are two functional scotomata corresponding to these areas. The eccentric scotoma is located on the nasal retina in esotropes; the greater the deviation, the larger the extent of the scotoma.11 This “adaptive” suppression of both the centric and eccentric retinal regions of the deviated eye could lead to neuronal modifications of afferent projections from these retinal sites, the consequences of which could account for the reduced nasal CSF’s demonstrated by the 20/300 amblyope in the present investigation.

Conclusion

The results of this investigation demonstrated that CSF results obtained from the central and peripheral retinas display characteristic changes with eccentricity. It might be suggested that these CSF changes reflect mediation by receptive fields of increasing dimensions; that is, CSF results obtained in the periphery reflect activity of neural channels characterized by relatively larger receptive field dimensions. The CSF changes may be summarized as follows: (1) overall reduction in function sensitivity, (2) peak sensitivity shift towards the lower spatial frequencies, and (3) a reduction in the cut-off frequency for the detection of both pattern and flicker.

Amblyopic CSF’s obtained from the central retinal region resembled those functions which might be obtained from a nonamblyopic peripheral site (the extent of which depended upon amblyopic acuity). Amblyopia resulting from esotropia left uncorrected during early childhood may reflect a visual system with a relatively “immature” receptive field organization. The inexperienced visual system of kittens contains neurons with diffusely organized (larger) receptive fields.13 Given “appropriate” visual experience, the neurons develop in such a way that receptive fields mature and become “tightly” organized. Since these neurons underlie the detection of pattern, it might be that the amblyopic CSF’s reflect activity of a relatively immature visual system.

REFERENCES

6. Tolhurst, D. J.: Separate channels for the analysis of


15. Blakemore, D., and Van Sluyters, R. C.: Reversal of the physiological effects of monocular deprivation in...