Contrast sensitivity in amblyopia due to stimulus deprivation

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SUMMARY Contrast sensitivity functions for sinusoidal gratings of varying spatial frequency and stimulus duration were determined for both eyes of 2 patients with amblyopia due to early occlusion and lid closure. The amblyopic eyes showed reduced contrast sensitivity over a wide range of spatial frequencies and stimulus durations, and the temporal integration time of the amblyopic eye was increased by comparison with the non-amblyopic eye at high spatial frequencies. When the gratings were flickered at 10 Hz the sensitivity for both flicker and pattern detection was reduced in the amblyopic eye over the entire spatial frequency range. Abnormal flicker perception by the amblyopic eyes was also evident in the reduced photopic luminosity functions of these patients.

Amblyopia is a condition in which there is a decrease in visual acuity caused by form deprivation and/or abnormal binocular interaction for which no organic cause can be detected by the physical examination of the eye and which in appropriate cases is reversible by therapeutic measures (von Noorden, 1977). Much of what is currently known about the effects of form deprivation, strabismus, and anisometropia on the developing nervous system comes from electrophysiological studies of cats or monkeys reared with experimentally induced amblyopia. These experimental manipulations result in marked disruption in cortical physiology, cell shrinkage in the LGN, and severe amblyopia (Wiesel and Hubel, 1963; von Noorden, 1977). However, it is not clear whether strabismus and form deprivation (due to lid suture or occlusion) affect similar cell populations in the visual pathway. There is evidence that the effects of monocular lid closure are selective for the Y or transient cells (Sherman *et al.*, 1972), while in kittens reared with unilateral strabismus the X or sustained cells appear to be most affected (Ikeda and Wright, 1976).

Amblyopia due to strabismus or anisometropia in man, has been much studied both psychophysically and electrophysiologically. In amblyopias of this type the 'light-sense' of the amblyopic eye is generally considered to be normal. Wald and Burian (1944) investigated dark adaptation and scotopic and photopic luminosity in persons with strabismic amblyopia and showed that these functions are

similar in amblyopic eyes and non-amblyopic eyes, the similarity indicating that the visual receptors function normally in the amblyopic eye. From these data they postulated a dissociation of form vision and light perception. Burian (1969) suggested that amblyopia represents a defect of form vision at photopic levels, which may be explained by a reduction in the lateral inhibition which is necessary for visual acuity but not for simple light perception. Visual evoked response (VER) studies of strabismic and anisometropic amblyopia similarly suggest that the responses to unpatterned stimuli are relatively unaffected in the amblyopic eye, while pattern responses are markedly abnormal (Spekreijse *et al.*, 1972; Sokol and Bloom, 1973; Levi, 1975; Levi and Walters, 1977). On the other hand several investigations (Awaya *et al.*, 1973; Tsutsui *et al.*, 1973; Levi, 1976) have shown that VERs elicited by both patterned and unpatterned stimuli may be abnormal in amblyopia due to form deprivation.

In order to understand better the nature of amblyopia of varying aetiologies it is important to characterise the performance properties of such eyes to a wide range of spatially and temporally modulated stimuli.

It has recently been reported that persons with naturally occurring amblyopia due to strabismus and/or anisometropia show abnormal contrast sensitivity over a wide range of spatial frequencies, with the deficit being most evident at high spatial frequencies (Levi and Harwerth, 1977; Hess and Howell, 1977), and these findings are reflected in the VER at suprathreshold contrast levels (Levi and Harwerth, 1978). When gratings are temporally

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modulated, either in counterphase or flickered, both flicker and pattern detection are similarly affected in the amblyopic eye (Hilz *et al.*, 1977; Levi and Harwerth, 1977; Wood and Kulikowski, 1978); however, for low spatial frequency gratings, at high rates of temporal modulation (for example, 10 Hz), both the flicker and pattern thresholds of the amblyopic eye are fairly similar to those of the non-amblyopic eye.

So far there have been no detailed psychophysical investigations of patients with amblyopia due to form deprivation. Here we present the results of studies of spatial and temporal processing in 2 patients with amblyopia due to form deprivation in order to characterise their performance properties and to ascertain whether the visual deficits resulting from form deprivation are similar in nature to those found in strabismic and anisometropic amblyopia.

Patients and methods

The patients were 2 young adults with unilateral amblyopia due to form deprivation. Both had clear media and normal fundi, and were appropriately corrected for refractive error. Detailed histories were available for both.

Patient *A*, male, aged 23, had a congenital ptosis of the left eye. Surgery at the age of 2 years was unsuccessful, and it was not until aged 6 that the condition was surgically corrected. A careful case history, ophthalmological records, and examination of early photographs suggested that during this period the eye was essentially closed. The Snellen acuity of the amblyopic eye was 20/100. Therefore the primary aetiological factor in this patient appeared to be lid closure.

Patient *B*, female, aged 29, was a congenital right esotrope. At age 9 months a programme of constant, total, direct occlusion of the left eye (that is, the non-deviating eye) was instituted. The patient wore a black patch 24 hours a day except for occasional visits to the eye specialist. The patch was changed in the dark. Strabismus surgery to the right eye was performed at age 11 months, and occlusion was continued for a further period of 11 months. Her Snellen acuity at the time of these investigations was 20/200 with the left eye, which was presumably a result of the prolonged occlusion early in life. While the period of susceptibility to the effects of monocular occlusion is not well defined in man, it appears to extend until at least 4 years of age (von Noorden, 1973). In addition the patient's left eye presently shows 12Δ of exotropia. Both patients had unsteady fixation (particularly patient *B*) but were capable of central fixation.

The methods used were similar to those in our study of strabismic and anisometropic amblyopia

(Levi and Harwerth, 1977). Gratings with a sinusoidal light distribution were electronically generated on an oscilloscope (Tektronix 5103N with P4 phosphor) by the method described by Campbell and Green (1965). A gate to the Z axis allowed the gratings to be presented intermittently, while maintaining a constant mean luminance (10 cd/m²). The screen was viewed at a distance of 114 cm and a circular mask provided a 3° field surrounded by a cone which was similar in colour and brightness to the screen.

At each spatial frequency the contrast was adjusted from below threshold in 1-db steps until threshold was reached. For each contrast threshold the series of 8 measurements yielded a standard error of less than 5%. To investigate spatiotemporal effects the gratings were presented either continuously or intermittently for durations of 500, 50, or 8 ms, at a rate of 1 per second, or were flickered at a rate of 10 Hz with an equal duty cycle.

Results

Fig. 1 shows the contrast sensitivity functions for both eyes of both patients for 4 different temporal conditions. The gratings were on continuously for 500, 50, and 8 ms. For both the non-amblyopic and amblyopic eyes it is apparent that contrast sensitivity is a function of stimulus duration and that the low spatial frequency attenuation diminishes with shorter stimulus duration. The contrast sensitivity function of the amblyopic eyes differs from that of the non-amblyopic eye in several respects. (1) Contrast sensitivity is reduced over a wide range of spatial frequencies and temporal durations. Only for the low spatial frequencies when the gratings were viewed continuously was the sensitivity of the amblyopic and non-amblyopic eyes similar, particularly the data of Patient *A*. (2) The peak sensitivity was shifted to the left, that is towards lower spatial frequencies. (3) The cut-off spatial frequency was shifted towards the lower spatial frequencies. The inset curves in Fig. 1 show log of ratio of contrast sensitivity of the 2 eyes as a function of spatial frequency. For all 4 stimulus durations the magnitude of the difference between the contrast sensitivity of the non-amblyopic and amblyopic eyes increases as a function of spatial frequency, although less markedly for Patient *B* than for Patient *A*.

To assess further the effects of stimulus duration we determined the contrast sensitivity for gratings of 0.50 cycles per degree (cpd) and 5.0 cpd at 9 different stimulus durations from 6.2 to 500 ms, as well as during continuous viewing of the gratings. Fig. 2 shows a plot of the contrast sensitivity of Patient *A* as a function of stimulus duration on

Fig. 1 Contrast sensitivity functions for Patient A (A) and Patient B (B). The open circles are the data for the non-amblyopic eye, closed circles show the data for the amblyopic eye. The duration of the stimulus is, from left to right, continuous, 500, 50, and 8 ms. The inset curves show the log of the ratio of the contrast sensitivity of the amblyopic to the non-amblyopic eye as a function of spatial frequency

log-log co-ordinates. Fig. 2A is for a 0.50 cpd grating, and Fig. 2B for a grating of 5.0 cpd. Each data point is the mean of 10 threshold measurements. For both spatial frequencies the data appear to be divided into 2 segments and straight lines were fitted to the data as previous investigators have done (Breitmeyer and Ganz, 1977). It is apparent that for both eyes contrast sensitivity increases as a function of stimulus duration and that the durations for which the contrast versus duration reciprocity holds is longer for 5.0 cpd than for 0.50 cpd (as indicated by the arrow). Breitmeyer and Ganz (1977) have similarly shown that integration time increases with the spatial frequency of the grating.

The effect of amblyopia on the reciprocity function also varies with spatial frequency. For the 0.50 cpd grating (Fig. 2A), the slopes of the reciprocity function and the integration time of the 2 eyes are similar, with the sensitivity of the amblyopic eye being uniformly reduced by approximately 2/10 log unit with respect to the non-amblyopic eye for most stimulus durations. When the gratings were on continuously, the sensitivity of the non-amblyopic eye was reduced while the sensitivity of the amblyopic eye was not diminished. Apparently, any temporal transient, regardless of duration, enhances the sensitivity of non-amblyopic eyes for low spatial frequency gratings.

Fig. 2B shows the data for a 5.0 cpd grating. For

this higher spatial frequency grating the data of the amblyopic eye differ from those of the non-amblyopic eye in 3 ways: (1) The slope of the accelerating portion of the curve is considerably lower; (2) the integration time of the amblyopic eye is approximately twice as long as that of the non-amblyopic eye; and (3) the contrast sensitivity of the amblyopic eye is greatly reduced by comparison with the non-amblyopic eye. This reduction varied from 7/10 log unit at short exposure durations to over 1 log unit at long exposure durations.

Thus the amblyopic eye shows reduced sensitivity to spatial contrast over a wide range of spatial frequencies and temporal durations, with the abnormality being most marked for high spatial frequencies. In addition, the temporal integration time for high spatial frequencies is greatly increased in the amblyopic eye, being approximately twice as long as that of the non-amblyopic eye.

When low spatial frequency sinusoidal gratings are alternated in counterphase or switched on and off repetitively at threshold, the spatial structure is not evident but rather there is an appearance of flicker or movement. If the contrast is increased further, the individual bars can be detected—the pattern recognition threshold (Van Nes *et al.*, 1967; Keesey, 1972; Kulikowski and Tolhurst, 1973). At higher spatial frequencies (greater than about 4 cpd) gratings which are temporally modulated at threshold

Fig. 2 Stimulus duration versus contrast sensitivity functions for the non-amblyopic (open circles) and amblyopic (closed circles) eyes of Patient A: (A) for a 0.5 cpd grating, (B) for a 5.0 cpd grating

appear indistinguishable from stationary gratings of similar spatial structure (Kulikowski and Tolhurst, 1973).

In order further to evaluate spatiotemporal properties in these patients, we determined contrast sensitivity functions for gratings which were switched on and off at a rate of 10 Hz using the method described by Kulikowski and Tolhurst (1973). The data are shown in Fig. 3. Data for the non-amblyopic eye are shown by the open symbols and for the amblyopic eyes by the solid symbols. The circles show the sensitivity for detecting the stimulus based on the appearance of flicker or movement. The triangles show the sensitivity for pattern recognition.

In Patient A (Fig. 3A) for both the amblyopic and non-amblyopic eyes it is clear that at low spatial frequencies detection (based on flicker or apparent movement) thresholds are lower (that is higher sensitivity) than the thresholds for pattern recognition, and show considerably less low frequency attenuation. Above spatial frequencies of 3 to 4 cpd, the patterns were recognisable at threshold and appeared to be stationary, and the contrast had to be further increased to determine flicker threshold

for high spatial frequency gratings. It is interesting that at all spatial frequencies tested both flicker detection and pattern recognition sensitivities of the amblyopic eye to the 10 Hz flickering stimuli are reduced approximately equally.

Both flicker and pattern detection thresholds were determined over the entire spatial frequency range for Patient B and the data are shown in Fig. 3B. For spatial frequencies below 3 cpd the non-amblyopic eye shows greater sensitivity to flicker than to pattern detection, while at higher spatial frequencies pattern recognition occurs at the detection threshold, and the contrast must be further increased for the flicker to be detected. The data for the amblyopic eye of Patient B are particularly interesting in that at all spatial frequencies above 0.50 cpd she was unable to reach pattern detection threshold. In addition, at all spatial frequencies flicker detection sensitivity was reduced in the amblyopic eye in contrast to that of the non-amblyopic eye.

To investigate further the low spatial frequency flicker responses of these patients we determined photopic luminosity curves, using a flicker criterion (Harwerth and Levi, 1978). The test field was 1° in

Fig. 3 Contrast sensitivity functions for Patients A and B for gratings flickering at 10 Hz. Flicker and pattern thresholds are shown for the non-amblyopic (open symbols) and amblyopic (closed symbols) eyes

diameter in a dark field with a 25 Hz flicker rate. The patient controlled an optical wedge which was varied to reach critical fusion frequency (CFF) in alternating ascending and descending trials. A total of 10 threshold values were obtained at each wavelength. The data for the 2 patients are shown in Figs. 4B and 4C respectively, while for comparison data from both eyes of an anisometropic amblyope are shown in Fig. 4A. The data for the non-amblyopic eyes are shown by the open circles and the data for the amblyopic eyes by the filled circles. The solid line is the Commission Internationale de l'Eclairage photopic luminosity curve for the standard observer.

It is interesting to note that for the patient with anisometropic amblyopia (OD 20/200, OS 20/20) the data for the 2 eyes are rather similar, while for

both patients with amblyopia due to form deprivation the data of the amblyopic eyes show a reduction in spectral sensitivity across all wavelengths.

Discussion

The results suggest that amblyopia due to form deprivation involves more than a simple reduction in detection of high spatial frequencies, since the reduction in contrast sensitivity of the amblyopic eye

Fig. 4 Photopic luminosity functions for anisometropic amblyope (A), and for Patient A (B) and Patient B (C). The open circles show the data for the non-amblyopic eyes and the filled circles are the data for the amblyopic eyes. The lines are the CIE photopic luminosity curve for the standard observer

is also evident for middle and low spatial frequencies and a wide range of temporal conditions. In addition, the temporal integration time of the amblyopic eye for high spatial frequency gratings is increased. The similarity of these deficits to those found in strabismic and anisometropic amblyopia suggest that there may be common aetiological factors in strabismic and anisometropic amblyopia and form deprivation amblyopia; however, the flicker data also suggest some differences in the performance characteristics of these different categories.

In the 2 patients studied the effects of lid closure and occlusion resulted in severe amblyopia with a loss of sensitivity to spatial contrast over a wide range of spatial frequencies. Their data differed from the strabismic and anisometropic amblyopes in that their contrast sensitivity functions did not show the reduction in low spatial frequency attenuation characteristic in the data of the strabismic and anisometropic amblyopes (Levi and Harwerth, 1977). In addition, the sensitivity to flickering gratings of low spatial frequencies was considerably reduced, whereas the strabismic and anisometropic amblyopes showed essentially identical pattern and flicker detection sensitivity for 0.50 cpd gratings flickered at a rate of 10 Hz; moreover, for Patient B we were unable to measure pattern detection thresholds for spatial frequencies above 0.50 cpd. The anomalous responses to low spatial frequency flickering stimuli were also reflected in their reduced photopic luminosity functions, while strabismic and anisometropic amblyopes showed essentially identical curves for the 2 eyes (Harwerth and Levi, 1978), a finding in agreement with those of Wald and Burian (1944). These data suggest the possibility of a more widespread deficit in amblyopia due to lid closure or occlusion, namely one involving both the pattern and luminance channels.

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