



Spatial Frequency Channels in Experimentally Strabismic Monkeys Revealed by Oblique Masking

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Although the spatial vision deficits of human strabismic amblyopes have been well documented, surprisingly little is known about the mechanisms underlying their visual performance. In an effort to reveal the structure underlying the spatial vision deficits associated with strabismic amblyopia, we measured the performance of monkeys (*Macaca nemestrina*) with experimental strabismus in a contrast detection task with oblique masks. The masks were two adjacent identical oblique sine-wave gratings modulated in space by a Gaussian envelope. The target stimulus was a vertically oriented Gabor patch that appeared superimposed on the center of either the left or the right mask. The animals were trained by operant methods to indicate the location of the target. We measured detection thresholds in each eye independently for a large number of test and mask spatial frequencies. For each test spatial frequency, detection thresholds were elevated in the presence of the mask. The threshold evaluations showed a peak for a particular spatial frequency that was typically similar to the test spatial frequency. This pattern of results is consistent with the idea that the tests are detected by a discrete number of channels tuned to a narrow range of spatial frequencies. The data from the deviated eyes did not appear qualitatively different from those of the fellow eyes, and could be accounted by the same number of channels in both eyes. Quantitative estimates of the channels' characteristics revealed that the channels derived from the deviated eyes' data were similar to those yielded by the fellow eyes, but showed a reduction in their sensitivity to contrast.

Strabismus Amblyopia Spatial frequency channels

INTRODUCTION

Amblyopia is a visual deficit of neural origin that usually results from abnormal early visual experience. The deficits in spatial vision of humans who become amblyopic as a result of early strabismus are relatively well described and include a constellation of resolution and sensitivity deficits (see Ciuffreda *et al.*, 1991 for a review). However, little is known about the mechanisms underlying the visual performance of strabismic amblyopes in these spatial vision tasks. Hess (1980) used the adaptation paradigm developed by Blakemore and Campbell (1969) to determine whether spatial frequency channels exist in the amblyopic visual system and to measure their properties. The main result of his experiments was that

the deviated eyes of strabismics with mild to severe amblyopia showed the same threshold elevation patterns as normal or non-deviated eyes. Hess therefore concluded that the amblyopic visual system contains discrete spatial frequency channels and that their bandwidths are similar to the normal ones. Based on further experiments Hess and Campbell (1980) concluded that the activity within a single channel was also normal, i.e. followed normal spatial summation characteristics at threshold, but that the interactions between the channels were anomalous (Hess, Burr & Campbell, 1980). These results are in agreement with a previous study by Levi, Harwerth and Smith (1979) who used dichoptic masking to investigate binocular interactions in subjects deprived of normal binocular vision. They showed that in two strabismic amblyopes, a masking grating presented in the amblyopic eye could mask the detection of a grating presented in the fellow eye and that this masking effect is spatial frequency, orientation and contrast dependent. Their results suggests the existence in strabismic amblyopes of mechanisms tuned to spatial frequency and orientation with characteristics similar to those found in normal subjects. They further reported (Levi &

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Harwerth, 1982) similar results using monoptic masking as well. Blake (1982) used band-limited noise to study spatial tuning in the two eyes of amblyopic subjects. Varying the noise spectrum allowed him to determine the bandwidth of the mechanisms responsible for the detection of a single grating. His results showed that amblyopes have detection mechanisms similar in bandwidth to those of normal subjects. Similar results were obtained by Nordmann, Freeman and Casanova (1992) using static random noise to mask the detection of static or drifting sinusoidal gratings. They showed that the presence of a broad-spectrum noise had identical effects on the detection of a single grating in normal and amblyopic subjects.

Monkeys with experimentally induced strabismus have been shown to develop deficits in spatial vision similarly to humans (von Noorden & Dowling, 1970; Harwerth, 1982; Harwerth, Smith, Boltz, Crawford & von Noorden, 1983a, b; Kiorpes, Carlson & Alfi, 1989; Kiorpes, Kiper & Movshon, 1993; Kiper, 1994; Kiper, Kiorpes & Movshon, 1994). In particular, monkeys with strabismic amblyopia show deficits in contrast sensitivity for a wide range of spatial frequencies (Harwerth, 1982; Harwerth *et al.*, 1983a; Kiorpes 1989; Kiper *et al.*, 1994). Since the contrast sensitivity function is often considered as an "envelope" around the individual sensitivities of discrete spatial frequency channels (see Graham, 1989), a detailed study of the channels' characteristics may provide an insight into the nature of the contrast sensitivity deficits of amblyopes. To more fully characterize the amblyopic deficits and to investigate their neural base, we tested several monkeys raised with experimental strabismus in an experiment designed to reveal the characteristics of their spatial frequency channels.

We used the "oblique masking" paradigm developed by Wilson, McFarlane and Phillips (1983) where the subjects have to detect a sinusoidal grating superimposed on a high contrast grating with a different orientation. The subjects' detection thresholds for targets of various spatial frequencies are measured as a function of the spatial frequency of the oblique mask. We found that the visual system of amblyopes contains a normal number of spatial frequency channels. These

channels appear to be normal in bandwidth but less sensitive to contrast than the normal ones.

SUBJECTS AND METHOD

We present data from four adult pigtail macaque monkeys (*Macaca nemestrina*). Three were made esotropic early in life by transection of the lateral rectus muscle and resection of the medial rectus muscle of the left eye (Kiorpes *et al.*, 1989). In addition, their left medial rectus muscle was advanced to the limbus. The three strabismic animals subsequently developed a loss of visual acuity in the deviated eye. The fourth subject was raised with normal visual conditions and is used for comparison. The subjects' type of strabismus, age of onset, refraction errors and angle of deviation are shown in Table 1. The clinical history of these subjects, behavioral measures of their visual capabilities and details of the behavioral testing methods have been published elsewhere (Kiorpes *et al.*, 1989, 1993; Kiper, 1994).

Briefly, the animals controlled stimulus presentations by placing their face in a face mask mounted on a testing cage. They viewed the display with their natural pupils and gave responses by pulling bars mounted inside the cage. The animals had restricted access to water outside of the testing room and correct responses during testing were rewarded by 0.25 cm³ of diluted (40%) apple juice, incorrect responses were followed by a tone and a timeout. The duration of the tone and timeout were under the experimenter's control and were adapted to optimize each animal's performance.

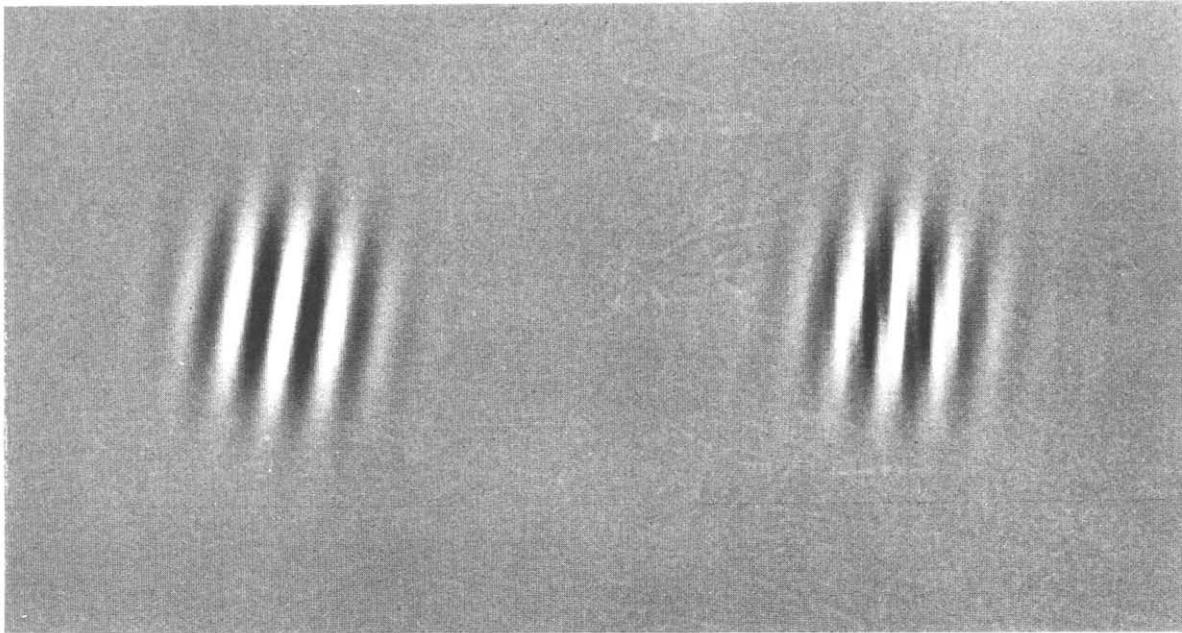
The stimuli were generated on a high resolution monitor (Mitsubishi HL6605) that subtended from 11.5 to 40 deg of visual angle depending on the viewing distance of the animal. They consisted of two identical oblique sine wave gratings modulated in space by a Gaussian envelope. These two masks were presented simultaneously side by side. The target stimulus, or test, appeared superimposed on the center of either the left or the right mask. The animal had to indicate the location of the target, which was a vertically oriented sine-wave grating modulated in space by a Gaussian envelope. The orientation of the masks was 12 deg away from vertical (randomly varied from trial to trial to be either clockwise

TABLE 1. Visual characteristics and spatial resolution of the subjects used in this study

Name		Age at surgery (days)	Last refraction (D)	Angle of esotropia (Prism D)	Spatial resolution (d/deg)
GH	Right eye	45	-0.50	19	29.7
	Left eye		+0.25		19.0
FT	Right eye	22	-3.25	23	21.6
	Left eye		-2.25		6.6
HC	Right eye	86	+0.255	11	24.2
	Left eye		+0.255		12.5
TJ	Right eye				17.9
	Left eye				18.0

The spatial resolution estimates were extrapolated from contrast sensitivity curves measured for each animal. The mean luminance of the display was 60 cd/m² and the targets were static sinusoids vignetted by a two-dimensional Gaussian window (Kiper *et al.*, 1994).

(a)



(b)

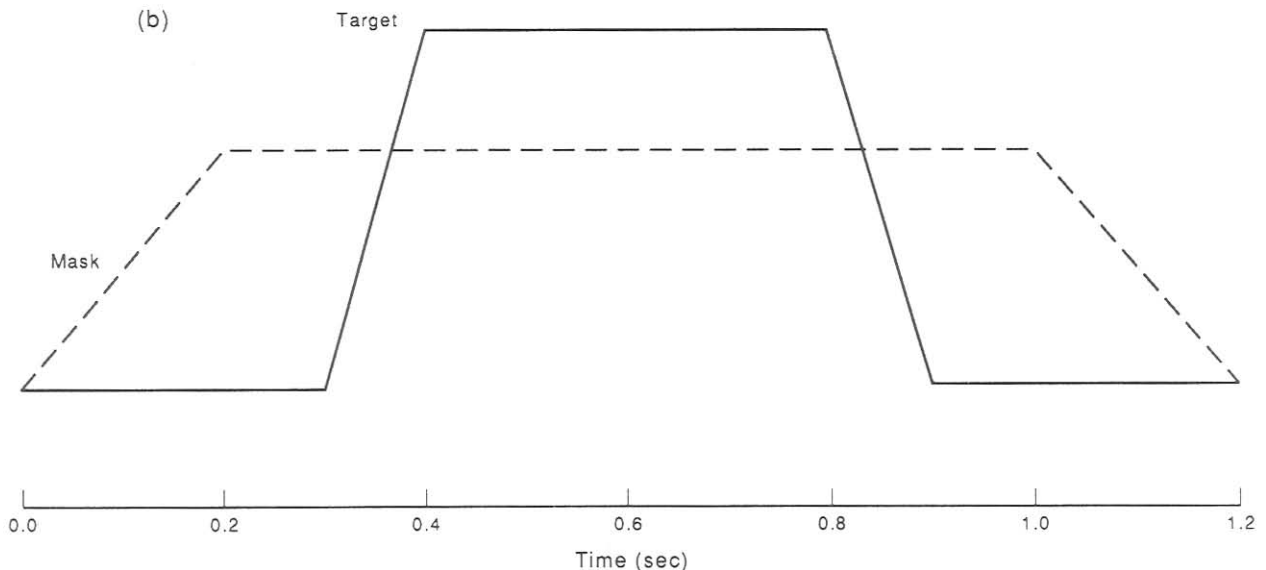


FIGURE 1. (a) Illustration of the stimuli. (b) Schematic showing the time-course of the stimulus presentation. The subjects had to indicate their response during a 1.5 sec period that immediately followed each trial.

or counterclockwise) and they had a contrast of 0.2. The SD of the Gaussians were 0.75 deg for the masks and 0.5 deg for the target. The space-averaged luminance of the stimuli was 60 cd/m², as was that of the uniform background (see Fig. 1). The presentation of the stimuli was limited in time as shown in Fig. 1.

After each trial, the animal had 1.5 sec to indicate the target's position. Any given session measured the effect of seven mask spatial frequencies on the detection of one test frequency. Three masks had spatial frequencies lower than the test's, chosen in approximately half-octave steps. One mask had the same spatial frequency and the three remaining had successively higher spatial

frequencies, also chosen in half-octave steps. Each block contained therefore 35 stimuli (5 target contrasts for each of the 7 masks) pseudorandomly interleaved. We measured masking effects of 5–9 different test spatial frequencies. To minimize phase effects, the relative phase between the target and the mask was randomized from trial to trial.

The data were collected using the method of constant stimuli. Psychometric functions were measured by presenting at least 40 trials for each stimulus in a randomized block design. We used a maximum likelihood method based on probit analysis (Finney, 1971) to fit the integral of a Gaussian to each set of data. This analysis

yielded estimates of thresholds and standard errors of the estimate for each condition. Threshold was defined as the 75% correct point.

RESULTS

Representative results for a normal subject and the fellow and amblyopic eyes of a strabismic are shown in Fig. 2. In each panel, the test spatial frequency is represented by the arrow on the abscissa. Each point in each panel represents the target's threshold elevation for a mask of a given spatial frequency relative to its unmasked threshold. In all cases, the threshold elevations showed a peak for a particular mask spatial frequency and decreasing elevations for different mask frequencies. This pattern of results has been taken as evidence for the existence of mechanisms mediating detection that are tuned to a narrow range of spatial frequencies (Legge & Foley, 1980; Wilson *et al.*, 1983). Note also that the magnitudes of threshold elevation are comparable between the normal, fellow and amblyopic eyes.

Data analysis

The results just described suggest that for the normal, fellow and deviated eyes of our monkeys, performance in this task is mediated by a discrete number of channels, each tuned to a narrow range of spatial frequencies. To obtain quantitative estimates of the channel charac-

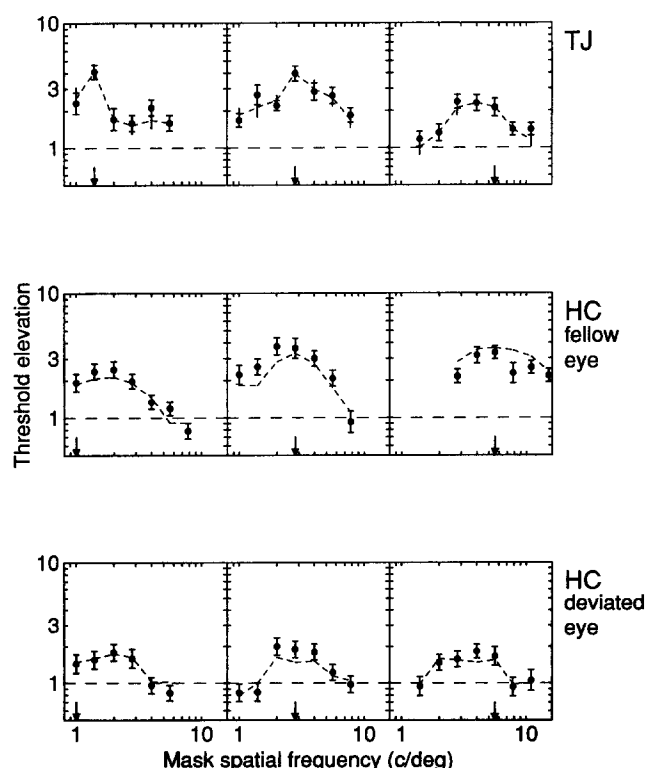


FIGURE 2. Representative data for the three test spatial frequencies (shown by the arrows) for the normal subject TJ, and the fellow and deviated eyes of one strabismic. Test spatial frequencies ranged from 1.0 to 15.0 c/deg. The data represent threshold elevations relative to the unmasked thresholds (dashed horizontal lines). The dashed curves fit to the data are the model predictions (see text).

teristics in the strabismic monkeys, it was necessary to make further assumptions and analyze these data accordingly.

The model used to analyze the data was proposed by Wilson *et al.* (1983) to analyze a similar experiment with human subjects. This model postulates three basic stages. First, the stimulus is processed by a number of linear spatial filters. The output of each filter is then processed by a non-linear contrast transducer. Then, uncorrelated noise is added to the outputs of the non-linear stage and the signals are fed to the third and last stage, the signal detector. The elements of this model are similar to those used by Legge and Foley (1980) in their study of contrast masking in human vision and to many other models of spatial vision (see Graham, 1989 for a review). Using the oblique masking data, this model can be used to compute each channel's sensitivity to all mask spatial frequencies (see Wilson *et al.*, 1983). However, our approach differed from that of Wilson's in the sense that we did not try to fit our data with the number of channels (N) as a free parameter. Briefly, in the method introduced by Wilson, the fitting procedure attempts to fit a subset of data with one channel and then, if necessary, keeps adding new channels as more subsets of data are processed. This has the disadvantage to yield different channel profiles depending on the order with which subsets of data are treated. We preferred to fix the number of channels, fit the model to the data and see how much of the variance in the data could be explained. We repeated this procedure for various values of N to determine what number of channels would allow to account for a significant proportion of the variance. The sensitivity profiles of the individual channels were then fitted with a truncated Gaussian function (± 2 SD). These fits allowed us to obtain estimates of channel bandwidths (bandwidth being defined as twice the standard deviation of the fitting Gaussian) and peak contrast sensitivities.

This analysis showed that for our subjects, and within the range of spatial frequencies used in these experiments, most of the variance in the data can be accounted for by postulating the existence of just three spatial frequency channels. Adding an additional channel does not significantly improve the model's predictions (e.g. for subject GH, the percentages of the variance explained by 1, 2, 3 and 4 channels were 40%, 55%, 81% and 83% respectively for the fellow eye, and 32%, 60%, 77% and 78% for the deviated eye). For the third subject, FT, two channels already account for most of the variance and adding more channels does not improve the fit. We also found that for each subject, the same number of channels in each eye is sufficient to account for the behavioral performance, suggesting that strabismic amblyopia does not fundamentally alter the basic organization of spatial filters. It is important to note however that our analysis does not exclude the possibility that more channels are actually present in the visual systems we studied. Indeed, other types of psychophysical experiments (see Graham, 1989 for a review) and physiological results (see De Valois & De Valois,

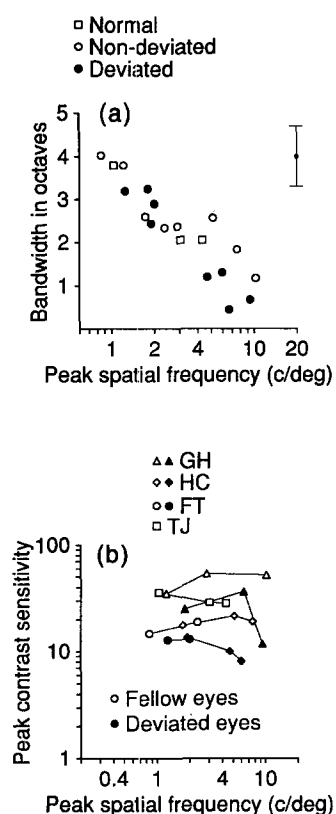


FIGURE 3. Mechanism characteristics obtained by fitting the data with the truncated Gaussian functions. (a) Bandwidth at half height as a function of peak spatial frequency. Open symbols are for the fellow eyes, solid symbols for the deviated eyes. The average SE of the estimates is shown in the upper right corner of the figure. (b) Mechanisms' peak contrast sensitivity as a function of peak spatial frequency. For each subject, the mechanisms derived from the deviated eye are less sensitive than those derived from the fellow eye.

1988 for a review) have shown that the visual system cannot always be simply described as a discrete set of independent filters. All we can conclude is that for this particular experiment, the same *minimal* number of channels is required in both eyes to fit the data. This is in good agreement with the results obtained by Hess (1980) with human subjects.

We used the channels derived by this model (three for HC and GH, two for FT) to predict the masking data and compare them to the measured data. The model predictions are shown by the dashed lines in Fig. 2. With few exceptions, these predictions fit the data quite well. Then, to obtain measures of the channels characteristics, we fitted the channels' sensitivity profiles with the truncated Gaussian function described above and obtained measures of bandwidth and peak sensitivity. The results are shown in Fig. 3. Figure 3(a) shows that the bandwidth of the channels derived in the amblyopic eyes (solid symbols) do not differ significantly from those obtained with the fellow eyes (open symbols). In Fig. 3(b) however, we see that for each animal, the channels derived in the deviated eye are less sensitive to contrast than those obtained in the fellow eye. This difference in contrast sensitivity is especially marked at high spatial frequencies.

DISCUSSION

The data obtained in these masking experiments suggest that the visual systems of the normal subjects as well as of the strabismic animals contain a discrete number of channels tuned to a narrow range of spatial frequencies. The data from all animals showed a characteristic pattern of threshold elevations, especially for low test frequencies. Our analysis showed that within the constraints imposed by the model, the same number of channels was sufficient to account for the masking data in the deviated and the fellow eyes. Estimates of the channels characteristics also revealed that the channels derived from the deviated eyes' data had similar bandwidths than those of the fellow eyes' but consistently lower contrast sensitivities, especially in the high spatial frequency range.

Our results suggest that the impaired capabilities in spatial vision tasks shown by monkeys with strabismic amblyopia can not be attributed to major abnormalities in the number and bandwidths of their spatial frequency channels. This is in agreement with the results of Hess (1980) with human subjects. Our results show however that some of the deficits of amblyopes can be attributed to a loss in the contrast sensitivity of the individual spatial frequency channels. Such a contrast processing loss has been proposed by several other authors to explain a variety of deficits shown by human strabismic amblyopes (Hess, 1982; Levi & Klein, 1990). Whether this loss is sufficient to account for all the behavioral deficits that have been described in the literature (see Ciuffreda *et al.*, 1991 for a review) remains unclear. Previous results with amblyopic monkeys (Kiorpes *et al.*, 1993; Kiper *et al.*, 1991, 1994) suggest that in addition to their contrast deficit, some additional factor contributes to their behavioral losses.

The similarity between the conclusions drawn from these experiments and those obtained from human subjects further validates the use of these animals as a model for human strabismic amblyopia. In addition to their well described impairment in contrast processing, more work is now needed to characterize specifically what additional factors contribute to the spatial vision deficits of strabismic amblyopes.

REFERENCES

- Blake, R. (1982). Binocular vision in normal and stereoblind subjects. *American Journal of Optometry and Physiological Optics*, 59, 969-975.
- Blakemore, C., Campbell, F. W. (1969). On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *Journal of Physiology*, 203, 237-260.
- Ciuffreda, K. J., Levi, D. M. & Selenow, A. (1991). *Amblyopia, basic and clinical aspects*. Oxford: Butterworth-Heinemann.
- De Valois, R. L. & De Valois, K. K. (1988). *Spatial vision*. Oxford Psychology Series 14. Oxford: Oxford University Press.
- Finney, D. J. (1971). *Probit analysis* (3rd edn). Cambridge: Cambridge University Press.
- Graham, N. (1989). *Visual pattern analyzers*. Oxford Psychology Series 16a. Oxford: Oxford University Press.

- Harwerth, R. S. (1982). Glenn Fry Award Lecture: Behavioral studies of amblyopia in monkeys. *American Journal of Optometry and Physiological Optics*, 59, 535–555.
- Harwerth, R. S., Smith, E. L. III, Boltz, R. L., Crawford, M. L. J. & von Noorden, G. K. (1983a). Behavioral studies on the effect of abnormal early visual experience in monkeys: Spatial modulation sensitivity. *Vision Research*, 23, 1501–1510.
- Harwerth, R. S., Smith, E. L. III, Boltz, R. L., Crawford, M. L. J. & von Noorden, G. K. (1983b). Behavioral studies on the effect of abnormal early visual experience in monkeys: Temporal modulation sensitivity. *Vision Research*, 23, 1511–1517.
- Hess, R. F. (1980). A preliminary investigation of neural function and dysfunction in amblyopia—1: Size selective channels. *Vision Research*, 20, 749–754.
- Hess, R. F. (1982). Developmental sensory impairment: Amblyopia or tarachopia? *Human Neurobiology*, 1, 17–29.
- Hess, R. F. & Campbell, F. W. (1980). A preliminary investigation of neural function and dysfunction in amblyopia—2: Activity within an amblyopic channel. *Vision Research*, 20, 755–756.
- Hess, R. F., Burr, D. C. & Campbell, F. W. (1980). A preliminary investigation of neural function and dysfunction in amblyopia—3: Co-operative activity of amblyopic channels. *Vision Research*, 20, 757–760.
- Kiorpes, L. (1989). The development of spatial resolution and contrast sensitivity in naturally strabismic monkeys. *Clinical Vision Sciences*, 4, 279–293.
- Kiorpes, L., Carlson, M. & Alfi, D. (1989). Development of visual acuity in experimentally strabismic monkeys. *Clinical Vision Sciences*, 4, 95–106.
- Kiorpes, L., Kiper, D. C. & Movshon, J. A. (1993). Contrast sensitivity and vernier acuity in amblyopic monkeys. *Vision Research*, 33, 2301–2311.
- Kiper, D. C. (1994). Spatial phase discrimination in experimentally strabismic monkeys. *Vision Research*, 34, 437–449.
- Kiper, D. C., Kiorpes, L. & Movshon, J. A. (1991). The relationship among spatial vision deficits of monkeys with experimentally induced strabismic amblyopia. *Investigative Ophthalmology and Visual Science (Suppl.)*, 32, 1044.
- Kiper, D. C., Kiorpes, L. & Movshon, J. A. (1994). Suprathreshold contrast sensitivity in experimentally strabismic monkeys. *Vision Research*, 34, 1575–1583.
- Legge, G. E. & Foley, J. M. (1980). Contrast masking in human vision. *Journal of the Optical Society of America*, 70, 1458–1471.
- Levi, D. M. & Harwerth, R. S. (1982). Psychophysical mechanisms in humans with amblyopia. *American Journal of Optometry and Physiological Optics*, 59, 936–951.
- Levi, D. M. & Klein, S. (1990). Equivalent intrinsic blur in amblyopia. *Vision Research*, 30, 1995–2022.
- Levi, D. M., Harwerth, R. S. & Smith, E. L. III (1979). Humans deprived of normal binocular vision have binocular interactions tuned to size and orientation. *Science*, 206, 852–854.
- Nordmann, J. P., Freeman, R. D. & Casanova, C. (1992). Contrast sensitivity in amblyopia: Masking effects of noise. *Investigative Ophthalmology and Visual Science*, 33, 2975–2985.
- von Noorden, G. K. & Dowling, J. E. (1970). Experimental amblyopia in monkeys II. Behavioral studies in strabismus amblyopia. *Archives of Ophthalmology*, 84, 206–214.
- Quick, R. F. (1974). A vector magnitude model for contrast detection. *Kybernetik*, 16, 65–67.
- Wilson, H. R., McFarlane, D. K. & Phillips, G. C. (1983). Spatial frequency tuning of orientation selective units estimated by oblique masking. *Vision Research*, 23, 873–882.

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