

Spatial vision deficit underlies poor sine-wave motion direction discrimination in anisometric amblyopia

Zhuping Qiu

School of Life Sciences and Research & Treatment Center of Amblyopia & Strabismus, USTC, Hefei, Anhui, China



Pengjing Xu

School of Life Sciences and Research & Treatment Center of Amblyopia & Strabismus, USTC, Hefei, Anhui, China



Yifeng Zhou

School of Life Sciences and Research & Treatment Center of Amblyopia & Strabismus, USTC, Hefei, Anhui, China, & State Key Lab of Brain and Cognitive Science, Institute of Biophysics, CAS, Beijing, China



Zhong-Lin Lu

Laboratory of Brain Processes (LOBES), Departments of Psychology and BME, USC, Los Angeles, CA, USA



For five anisometric amblyopes and five normal controls, contrast sensitivities in both grating motion direction discrimination and moving grating detection were measured with the same moving sine-wave stimuli over a wide range of spatial and temporal frequencies. We found that the apparent local motion deficits in anisometric amblyopia can be almost completely accounted for by deficits in moving grating detection. Furthermore, the differences between the amblyopic and the nonamblyopic eyes are nonspecific to temporal frequency in both motion direction discrimination and moving grating detection and are quantitatively identical to the differences in their contrast sensitivities. The observations on motion direction discrimination and its relationship to the contrast sensitivity function were replicated with an additional five anisometric amblyopes and four normal controls. Complementing an earlier study on strabismic amblyopia (R. F. Hess & S. J. Anderson, 1993), these results suggest that local motion-sensitive mechanisms are largely intact in anisometric amblyopia; the apparent local motion deficits in anisometric amblyopia can be modeled with deficits in contrast sensitivity functions.

Keywords: anisometric amblyopia, local motion, direction discrimination, detection, modulation transfer function

Citation: Qiu, Z., Xu, P., Zhou, Y., & Lu, Z. (2007). Spatial vision deficit underlies poor sine-wave motion direction discrimination in anisometric amblyopia. *Journal of Vision*, 7(11):7, 1–15, <http://journalofvision.org/7/11/7/>, doi:10.1167/7.11.7.

Introduction

Amblyopia is a developmental visual disorder that is usually defined as a deficit in optotype acuity without obvious structural or pathological ocular anomalies. Cannot be corrected by refractive means, amblyopia is mostly considered as a spatial vision deficit often associated with reduced contrast sensitivity (Ciuffreda, Levi, & Selenow, 1991; Hess & Howell, 1977; Levi, Klein, & Sharma, 1999) and poor spatial localization (Levi & Klein, 1982).

There is converging evidence that the primary visual cortex (V1) is the first site in the visual pathway that is affected by amblyopia. Whereas many studies found no significant change in the retina and the lateral geniculate nucleus in amblyopia (DeLint, Berendschot, & van Norren, 1998; Hendrickson et al., 1987; Movshon et al., 1987), there are reports of both reduced cellular contrast

sensitivity (Movshon et al., 1987) and a loss of the proportion of cells driven by the amblyopic eyes in the primary visual cortex of amblyopic monkeys (Kiorpes, Kiper, O'Keefe, Cavanaugh, & Movshon, 1998), as well as reduced fMRI activities (Barnes, Hess, Dumoulin, Achtman, & Pike, 2001) and significantly longer MEG response latencies and reduced amplitudes in the primary visual cortex of human amblyopes (Anderson, Holliday, & Harding, 1999).

It is still not entirely clear whether amblyopia affects the visual pathway beyond the primary visual cortex (Barnes et al., 2001; Daw, 1998; Kiorpes & McKee, 1999), although it has been suggested that neural deficits in amblyopia are not limited to neurons in V1 (Kiorpes et al., 1998), and disruption in the binocular organization of extra-striate cortical areas has been documented in amblyopic primates (Movshon et al., 1987) and cats (Schroder, Fries, Roelfsema, Singer, & Engel, 2002). A number of psychophysical studies have also reported that

amblyopia impairs visual functions that are known to involve higher cortical areas, including visual illusions (Poppel & Levi, 2000), individuation of features within an image (Sharma, Levi, & Klein, 2000), second-order perception (Mansouri, Allen, & Hess, 2005; Wong, Levi, & McGraw, 2001), contour integration (Hess & Demanins, 1998; Kozma & Kiorpes, 2003; Kovács, Polat, Pennefather, Chandna, & Norcia, 2000), global motion (Simmers, Ledgeway, & Hess, 2005; Simmers, Ledgeway, Hess, & McGraw, 2003), and motion aftereffects (Hess, Demanins, & Bex, 1997). A recent functional magnetic resonance imaging study also found decreased cortical activation in response to motion stimuli in anisometric amblyopic eyes (Bonhomme et al., 2006). However, the possibility has not been completely ruled out that some apparent mid and/or high level visual function deficits in amblyopia are caused by defective inputs to the higher level visual areas from the primary visual cortex. In several studies, the mid/high level deficits “disappeared” once the inputs to the higher level processes were equated between the normal and the amblyopic eyes (Hess, Mansouri, Dakin, & Allen, 2006; Mansouri et al., 2005; Simmers et al., 2005). In this study, we investigate effects of amblyopia on motion perception.

There is strong evidence that various types of amblyopia are deficient in global motion processing (Elleberg, Lewis, Maurer, Brar, & Brent, 2002; Kiorpes, Tang, & Movshon, 2006; Simmers et al., 2003). Using random dot kinematograms, Elleberg et al. (2002) found that the patients’ ability to discriminate the direction of global motion was significantly impaired after early visual deprivation, with much worse impairments after early binocular deprivation than monocular deprivation. Simmers et al. (2003, 2005) reported that both global orientation and global motion processing deficits in strabismic, anisometric, and strabismic/anisometric amblyopes, beyond any low-level visibility loss, with the most severe deficit affecting the extraction of global motion. In a newly published study, Kiorpes et al. (2006) measured visual motion sensitivity in monkeys with either strabismic or anisometric amblyopia using random dot kinematograms over a wide range of spatial displacements and temporal delays. The authors found that both types of monkey amblyopes were severely impaired in detecting global motion in fine spatial scale and slow speeds. Although the frequency shift of the motion sensitivity function of the amblyopes was correlated with that of their contrast sensitivity functions (CSFs), the losses in motion sensitivity were not correlated with losses in spatial contrast sensitivity. There were substantial deficits in spatiotemporal integration and motion perception in the amblyopic eyes.

Results from psychophysics (Morrone, Burr, & Vaina, 1995), electrophysiological recording and lesion studies on monkeys (Mikami, Newsome, & Wurtz, 1986a, 1986b; Newsome & Pare, 1988), functional imaging on humans (Sunaert, Van Hecke, Marchal, & Orban, 1999; Tootell

et al., 1995), and human lesion patient evaluations (Baker, Hess, & Zihl, 1991; Plant & Nakayama, 1993; Vaina, 1989; Vaina, Cowey, Eskew, LeMay, & Kemper, 2001) all suggest that global motion processing involves a two stage process: a local motion computation stage in V1 and a global integration stage in extra-striate cortical areas, such as MT and MST. The observed global motion deficits in amblyopia could in principle stem from deficiencies in either local motion computation, global integration, or a combination of the two. To fully understand the nature of motion perception deficits in amblyopia, we therefore must evaluate both stages of motion processing in that population. Using moving sine-wave gratings as motion stimuli in which the motion signals in all the “local” patches are consistent, the current study is primarily concerned with local motion processing in amblyopia.

Based on motion-onset visual evoked potentials recorded from 20 anisometric, 7 strabismic, and 10 anisometric/strabismic amblyopes, Kubová, Kuba, Juran, and Blakemore (1996) concluded that (local) motion perception is not impaired in amblyopia. Local motion processing in (mostly) strabismic amblyopia has also been systematically evaluated in a psychophysical study (Hess & Anderson, 1993). Moving sine-wave grating detection and direction discrimination thresholds over a wide range of spatial and temporal frequencies were measured for seven strabismic and one anisometric amblyopes. The authors found that the threshold differences in motion direction discrimination between the amblyopic and the normal eyes can be mostly accounted for by the threshold differences in moving grating detection between the two types of eyes, except over a narrow part of the visible range in the amblyopic eyes. They concluded that the observed local motion deficits (as reflected in the elevated motion direction discrimination thresholds) in (mostly) strabismic amblyopia are due to deficient spatial vision, as reflected in the elevated moving grating detection thresholds; motion-sensitive mechanisms are not selectively affected in amblyopia.

In a highly related line of research on temporal perception, Bradley and Freeman (1985) measured flicker sensitivity in both strabismic and anisometric amblyopia for a wide range of spatial and temporal parameters. Together with another study by Bradley and Freeman (1981) on spatial contrast sensitivity in anisometric amblyopia, they concluded that the presence or the absence of reduced sensitivity to flicker stimuli mainly depended on the spatial deficits in amblyopia. Manny and Levi (1982b) reported that the critical fusion frequency of the amblyopic eye was equal to that of the nonamblyopic eye or was only slightly reduced. Although related, these studies on temporal perceptual may not directly inform us of motion deficits in amblyopia.

The current study complements that of Hess and Anderson (1993). Whereas Hess and Anderson focused

mostly on strabismic amblyopia, we evaluated deficits of local motion perception in 10 anisometric amblyopes. The independent evaluation of local motion perception deficits in anisometric amblyopia is important even after the publication of the comprehensive study of Hess and Anderson on strabismic amblyopia, not only because the two types of amblyopia are of different pathological origins, but also because there exist important differences in global motion deficits in the two types of amblyopia (Kiorpes et al., 2006), and the one anisometric amblyope in Hess and Anderson behaved somewhat differently from the strabismic amblyopes: Whereas strabismic amblyopes exhibited local motion processing deficits in a narrow range of spatial–temporal frequencies, the anisometric amblyope exhibited no local motion processing deficits in the entire range of the tested spatial and temporal frequencies.

The basic design of our study is the same as that of Hess and Anderson (1993). Specifically, we measured contrast sensitivities for both motion direction discrimination (Figure 1a) and moving grating detection (Figure 1b) with the same moving sine-wave grating stimuli over a wide range of spatial and temporal frequencies. Although the same motion stimuli were used in the moving grating detection experiment, the task did not require any motion computation and can be used as a baseline control for the detectability of the moving sine-wave gratings. On the other hand, the motion direction discrimination task required motion-sensitive mechanisms. Only losses of motion direction discrimination sensitivity beyond those of grating detectability should be attributed to deficits in local motion perception. If there were no local motion perception deficit in anisometric amblyopia, we would expect that the ratio between the contrast sensitivities in

motion direction discrimination and that in moving grating detection to be 1.0 in all spatial and temporal frequencies (Figure 1c).

Method

Subjects

Ten 18- to 25-year-old unilateral anisometric amblyopes (three males and seven females, average age = 19.7 ± 1.25 years) with appropriate optical corrections participated in the study. Five of them ran all the tests and the other five graduated from and left the university after only finishing the CSF and motion direction discrimination tasks. All the amblyopic subjects had central fixation without any strabismic component. Two of them (W. Q. M. and G. J. Y.) had been treated with the occlusion therapy. The ophthalmologic characteristics of all the amblyopic observers are listed in Table 1.

Nine adults with normal or correct-to-normal vision (five males and four females, average age = 22.6 ± 2.7 years) served as normal controls. Five of them ran all the tests and the rest four only finished the CSF and motion direction discrimination tests before they graduated and left the university.

All observers, naive to the purpose of the experiment, were given written informed consent.

Apparatus and stimuli

The stimuli were displayed on a Sony G220 monitor (refresh rate = 160 Hz) driven by an ATI 7500 video card in a PC. They were generated in real time using Matlab

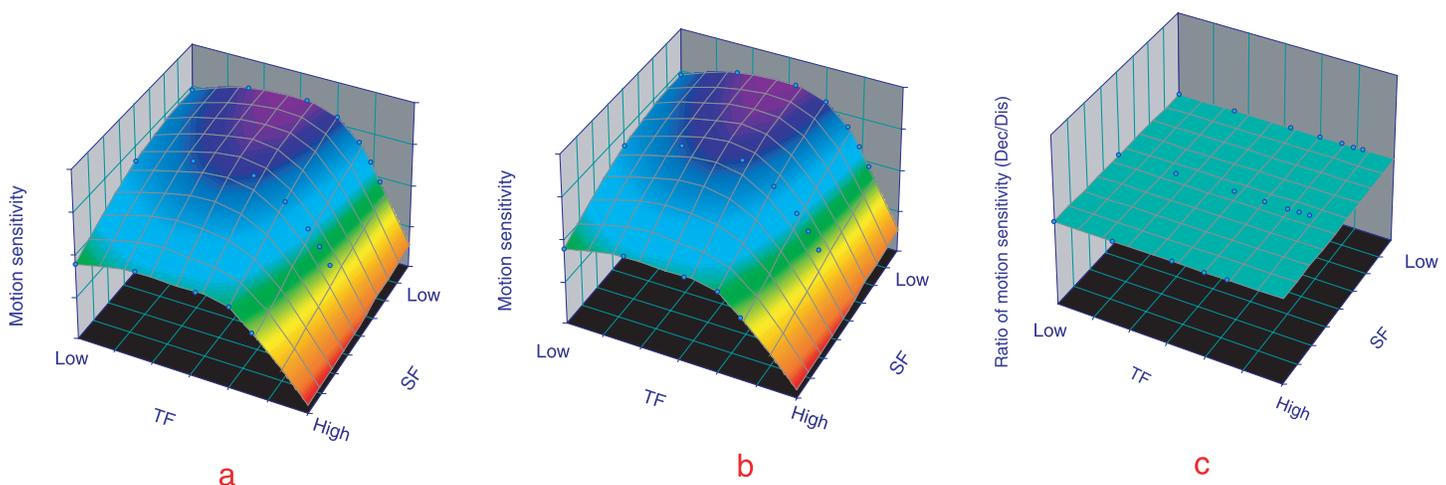


Figure 1. Schematic diagrams of spatial–temporal contrast sensitivity surfaces in amblyopia. (a) A spatial–temporal contrast sensitivity surface of motion direction discrimination in AE. (b) A spatial–temporal contrast sensitivity surface of moving grating detection in AE. (c) The ratio of the two surfaces in panels a and b. AE, amblyopic eyes; Dis, motion direction discrimination; Dec, moving grating detection.

Subject	Gender	Age	Type	Optical correction	Visual acuity (MAR)
W.Q.M.	M	22	A	AE +3.50	1.7
				NAE Plano	0.8
H.H.X.	F	18	A	AE +6.00	5.0
				NAE Plano	0.7
G.J.Y.	F	18	A	AE +3.50	2.5
				NAE Plano	1.0
C.C.K.	M	21	A	AE +4.75/+0.75 × 80	5.0
				NAE +1.00	1.0
S.Y.	F	19	A	AE +4.00+1.50 × 100	3.3
				NAE Plano	1.0
C.M.N.	F	19	A	AE +6.00/+0.75 × 42	4.0
				NAE -0.75/-0.50 × 161	1.0
H.C.Y.	F	20	A	AE +6.00/+2.00 × 175	1.7
				NAE -1.50	0.8
Z.Q.	M	20	A	AE +1.00/+2.00 × 170	10.0
				NAE -1.75	0.7
G.Z.G.	M	20	A	AE +3.50	3.3
				NAE Plano	1.0
X.Y.X.	F	20	A	AE +6.75	5.0
				NAE Plano	1.0

Table 1. Characteristics of the amblyopic observers. F, female; M, male; A, anisometric amblyopia; AE, amblyopic eye; NAE, nonamblyopic eye; MAR, minimum angle of resolution. The first five subjects participated in all the procedures; the last five subjects only participated in the contrast sensitivity function (CSF) and the motion direction discrimination tests.

programs based on Psychtoolbox version 2.50 (Brainard, 1997; Pelli, 1997) and were viewed monocularly in a dimly lit room. A special circuit (Li, Lu, Xu, Jin, & Zhou, 2003) was used to produce 14 bits of gray levels. The background luminance of the display was set in the middle of luminance range of the monitor, 27 cd/m².

Vertical stationary sine-wave gratings were used to measure CSFs at six spatial frequencies (0.5, 1, 2, 4, 8, and 12 c/deg) in the amblyopic eyes (AE) and seven spatial frequencies (0.5, 1, 2, 4, 8, 12, and 16 c/deg) in the nonamblyopic eyes (NAE) of the amblyopic subjects and the dominant eyes (CE) of the normal control subjects. They were presented in a circular window in the center of the display and viewed at a distance of about 2.28 m. The central portion (radius $\leq 1^\circ$) of the circular window was flat. The fringe (radius $> 1^\circ$) of the window gradually blended into the background via a Gaussian ramp with $\sigma = 0.5^\circ$. The diameter of the circular window was 2° .

Drifting sine-wave gratings in a wide range of spatial and temporal frequencies were used to measure contrast thresholds in motion direction discrimination and moving grating detection:

$$L = L_0 \{1 + c \sin[2\pi(fx \pm \omega t) + \phi]\}, \quad (1)$$

where L_0 is the background luminance of the display, c is the contrast of the grating, f is the spatial frequency of the grating, ϕ is the (random) initial spatial phase, and ω is the temporal frequency. Viewed at a distance of about 1.14 m, the gratings subtended 2.0° by 2.0° .

In both motion direction discrimination and moving grating detection tests, for each amblyopic observer, contrast sensitivity over a range of temporal frequencies was measured at three spatial frequencies: a low spatial frequency of 0.25 c/deg, an intermediate spatial frequency, defined as the geometric mean of the optimal spatial frequencies of the amblyopic and the nonamblyopic eyes obtained from the CSF measurements, and a high spatial frequency, defined as the spatial frequency at which the contrast threshold is 10% in the amblyopic eye on the CSF. For the control subjects, 0.25 c/deg, the optimal spatial frequency of the dominant eye, and the average high spatial frequency of the amblyopes were used. The low, the intermediate, and the high spatial frequencies for each individual observer are listed Table 2. Six temporal frequencies (3, 9, 16, 24, 30, and 36 Hz) were studied in all the spatial frequency conditions in the control eyes and the nonamblyopic eyes. But for amblyopic eyes, only four temporal frequencies (3, 9, 16, and 24 Hz) were tested in the high spatial frequency condition, five temporal frequencies (3, 9, 16, 24, and 30 Hz) in the intermediate SF condition, and six temporal frequencies (3, 9, 16, 24, 30, and 36 Hz) in the low spatial frequency condition.

Procedure

A two-interval forced choice (2IFC) task was used to measure CSFs. In each trial, the signal stimulus was

Subject		Low SF	Optimal SF (AE)	Optimal SF (NAE)	Intermediate SF	High SF
Amblyope	W.Q.M.*	0.25	2.0	2.0	2.0	8.5
	H.H.X.*	0.25	0.5	4.0	1.0	3.0
	G.J.Y.*	0.25	0.5	1.0	2.0	9.0
	C.C.K.*	0.25	1.0	2.0	1.4	9.0
	S.Y.*	0.25	1.0	1.0	1.0	4.0
	C.M.N.	0.25	1.0	2.0	1.4	5.0
	H.C.Y.	0.25	1.0	0.5	0.7	5.0
	Z.Q.	0.25	0.5	2.0	1.0	8.0
	G.Z.G.	0.25	2.0	2.0	2.0	9.0
	X.Y.X.	0.25	1.0	2.0	1.4	2.5
Normal	C.B.*	0.25		1.0		5.0
	L.L.*	0.25		1.0		5.0
	Q.Z.P.*	0.25		2.0		5.0
	P.Z.Z.*	0.25		2.0		5.0
	Z.B.B.*	0.25		2.0		5.0
	L.L.I.	0.25		1.0		5.0
	M.J.	0.25		4.0		5.0
	Z.X.X.	0.25		2.0		5.0
	Z.Y.	0.25		1.0		5.0

Table 2. Low, intermediate, and high spatial frequencies (c/deg) for the amblyopic and the normal subjects. For amblyopes, the intermediate spatial frequency is defined as the geometric mean of the optimal spatial frequencies of the amblyopic eye (AE) and the nonamblyopic eye (NAE) on the contrast sensitivity function (CSF); the high spatial frequency is defined as the cutoff spatial frequency associated with a contrast threshold of 10% in the amblyopic eye on the CSF. For normal control subjects, the “intermediate spatial frequency” is their optimal spatial frequency, and the high spatial frequency was selected as 5 c/deg, the mean cutoff spatial frequency of the amblyopic eyes. Asterisk (*) indicates subjects who participated in all the procedures.

randomly presented in one of the two successive presentation intervals (signaled by a “beep” in the beginning of each interval) each lasting 125 ms and separated by a 500-ms interstimulus interval. The observer was required to press a button to indicate which presentation interval contained the signal. Contrast thresholds were measured using the two-down one-up staircase procedure (Levitt, 1971), which decreased the signal contrast by 10% ($c_{t+1} = 0.90 c_t$) following every two consecutive correct responses and increased the signal contrast by 10% ($c_{t+1} = 1.10 c_t$) after each incorrect response, converging on 70.7% correct. Each staircase ran through 84 trials, usually generating about 20 reversals. The average contrast at the reversals was calculated, after excluding the first two or three depending on whether an even or an odd number of reversals was obtained to estimate the threshold contrast.

For the amblyopes, CSFs were measured in both the amblyopic and the nonamblyopic eyes in separate 40-min sessions. The order was counterbalanced across subjects. For the control subjects, CSF was only measured in the dominant eyes. All the spatial frequencies were randomly mixed in each session.

Motion direction discrimination thresholds were measured with a two-alternative forced identification method. In each trial, a drifting sine-wave grating with a randomly

chosen leftward or rightward motion direction was presented for 250 ms, with 25-ms linear ramps in the beginning and the end. The observer was asked to determine whether the grating drifted to the left or to the right. The same two-down one-up staircase procedure was used to track the threshold contrast at 70.7% correct.

The procedure used to measure moving grating detection thresholds was similar to that of the CSF test. In each trial, the signal stimulus (a 250-ms moving sine-wave grating with 25-ms linear ramps in the beginning and the end) was randomly presented in only one of two successive presentation intervals separated by a 500-ms interstimulus interval. The observer was also asked to press a button to indicate which presentation interval contained the signal. Again, the two-down one-up staircase procedure was used to track the threshold contrast at 70.7% correct.

For the amblyopes, motion direction discrimination and moving grating detection thresholds were measured in both the amblyopic and the nonamblyopic eyes in separate sessions. The order was counterbalanced across subjects. For the control subjects, the thresholds were only measured in the dominant eyes. Measurements were blocked by eye and spatial frequency. For a given spatial frequency, all the temporal frequencies were intermixed. In the motion direction discrimination test, subjects

finished three sessions in one eye before they switched to the other eye. Each session lasted 40 min. Ascending spatial frequencies were used in each eye in the three sessions. The same schedule was used for the moving grating detection test.

Model fitting and statistics

The CSFs were fitted with the difference of Gaussian (DOG) function (Rohaly & Buchsbaum, 1988, 1989; Xu, Lu, Qiu, & Zhou, 2006)

$$\log(S_t) = a_1 \exp \left[- \left(\frac{\log_2(f) - b_1}{c_1} \right)^2 \right] - a_2 \exp \left[- \left(\frac{\log_2(f) - b_2}{c_2} \right)^2 \right], \quad (2)$$

where f is the spatial frequency of the sine-wave grating, S_t is the predicted contrast sensitivity, and a_1 , b_1 , c_1 , a_2 , b_2 , and c_2 are the parameters. The same formula was also used to fit the temporal modulation functions at each spatial frequency, where f denotes temporal instead of spatial frequency.

Our model fitting procedure was implemented in Matlab with the curve fitting toolbox. The sum of the squared

differences ($\sum \text{sqdiff} = \sum [\log(S_t) - \log(S_{\text{measured}})]^2$) between the log measured sensitivities (S_{measured}) and the log model-predicted sensitivities (S_t) was minimized.¹ The goodness of fit for each model was determined by

$$r^2 = 1.0 - \frac{\sum \text{sqdiff}}{\sum \{ \log(S_t) - \text{mean}[\log(S_{\text{measured}})] \}^2}. \quad (3)$$

Within-subject analysis of variance (ANOVA) was used to compare data in the amblyopic and the nonamblyopic eyes of the amblyopic observers. Between-subject ANOVA was used to compare data in the amblyopic eyes of the amblyopic observers and the dominant eyes of the control subject and the nonamblyopic eyes of the amblyopic observers and the dominance eyes of the control subjects.

Results

Contrast sensitivity functions

The measured CSFs of the amblyopic eyes (AE), nonamblyopic eyes (NAE), and control eyes (CE), along with the best fitting DOGs for all 19 subjects are shown in Figure 2a. All the CSFs exhibited the conventional

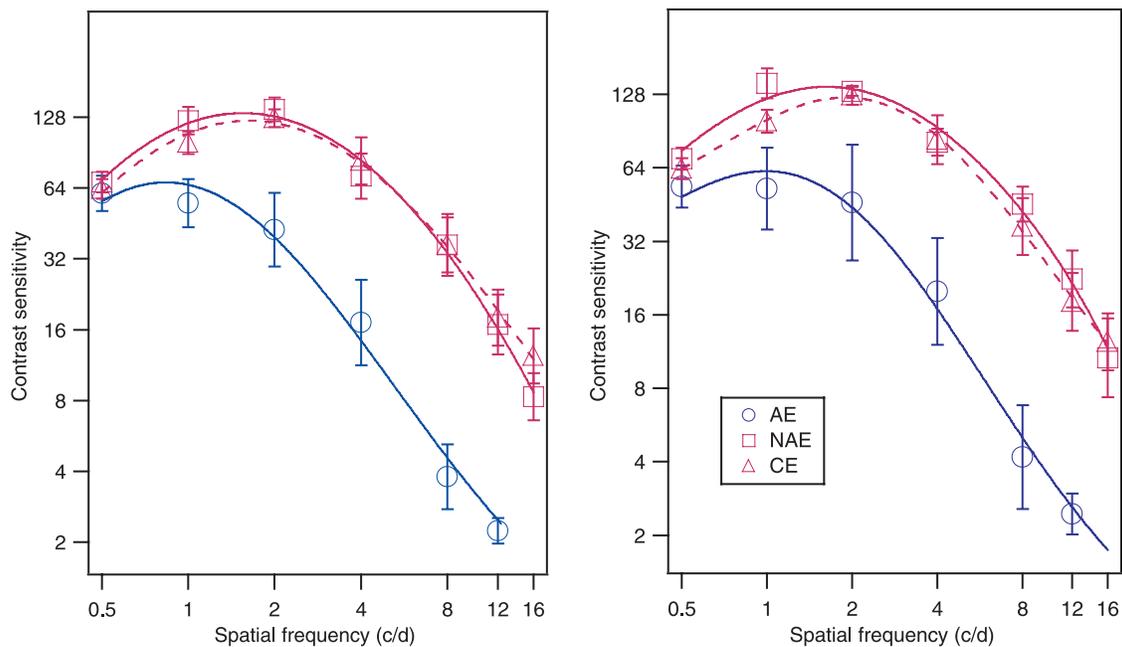


Figure 2. Average contrast sensitivity functions (CSFs) of the amblyopic eyes (AE), the nonamblyopic eyes (NAE), and the control eyes (CE) (circles: AE; squares: NAE; triangles: CE). (a) The average CSFs of all the 10 amblyopic and the 9 normal subjects. (b) The average CSFs of the five amblyopic and the five normal subjects who ran all the procedures. The blue solid, red solid, and red dashed curves represent the predictions of the best fitting DOGs. The error bars represent one standard error.

band-pass shape. There was no significant difference between the CSF of the nonamblyopic eyes and the control eyes, $F(1, 17) = 0.005, p > .9$, whereas the CSFs of the amblyopic eyes were significantly lower than those of the nonamblyopic eyes, $F(1, 9) = 34.8, p < .01$.

We computed the optimal spatial frequency—the spatial frequency corresponding to the maximum contrast sensitivity for the amblyopic eyes, the nonamblyopic eyes, and the control eyes. The results are listed in Table 2. The average optimal spatial frequency was $1.1 \pm 0.2, 1.9 \pm 0.3$, and 1.8 ± 0.3 c/deg for AE, NAE, and CE, respectively. We also calculated the cutoff spatial frequencies of the amblyopic eyes, which were defined as the spatial frequency at which contrast threshold is equal to 10% (Table 2). For the amblyopes, the average cutoff spatial frequency was 5.0 ± 1.0 c/deg.

The degree of CSF deficit depended strongly on the spatial frequency. At the low spatial frequency (0.25 c/deg), the contrast sensitivity of the nonamblyopic eyes was much closer to that of the AE (CS (NAE) / CS (AE) = 1.1 ± 0.2). At the optimal spatial frequencies, the contrast sensitivity ratio between the nonamblyopic eyes and the amblyopic eyes increased to 2.4 ± 0.6 . At the high spatial frequency (5 c/deg), the contrast sensitivity ratio between the nonamblyopic and the amblyopic eyes further rose to 7.1 ± 1.7 . That the CSF deficits varied as an increasing function of spatial frequency is consistent with many reports in the literature (Asper, Crewther, & Crewther, 2000; Hess & Howell, 1977; Howell, Mitchell, & Keith, 1983).

Based on the CSF measurements, we selected three spatial frequencies for the motion direction discrimination and moving grating detection tests: 0.25 c/deg, an intermediate spatial frequency, and a high spatial frequency. For amblyopes, the intermediate spatial frequency was defined as the geometric mean of the optimal spatial frequencies of the amblyopic and the nonamblyopic eyes; the cutoff spatial frequency for each individual amblyopic subject was used as his or her “high” spatial frequency. For the control subjects, the optimal spatial frequency of the dominant eye was used as the intermediate spatial frequency (Table 2); we chose 5 c/deg, the average cutoff spatial frequency of the amblyopic subjects, as the “high spatial frequency.” The parameters of the best fitting DOGs are listed in Table 3a.

Motion direction discrimination versus moving grating detection

In this section, we present data from five anisometric amblyopes and five normal controls who participated in all the tests: CSF, motion direction discrimination, and moving grating detection. Their average CSFs, virtually identical to that of the 10 amblyopes and 9 controls, are plotted in Figure 2b.

The modulation transfer functions (MTFs) in the motion direction discrimination test are plotted in Figures 3a, 3b, and 3c. The MTFs exhibited no significant differences between the NAEs and the CEs in all the three tested spatial frequencies, $F(1, 8) = 1.83, p > .2$. At the low spatial frequency, the MTF of the AE showed no significant loss compared to that of the nonamblyopic eyes, $F(1, 4) = 0.13, p > .5$, whereas significant loss appeared at the intermediate, $F(1, 4) = 8.68, p < .05$, and high spatial frequencies, $F(1, 4) = 13.3, p < .03$. The parameters of the best fitting DOGs to the MTFs are listed Table 3b.

The ratios of motion direction discrimination sensitivity between the nonamblyopic and the amblyopic eyes are plotted as functions of temporal frequency for the three spatial frequencies in Figure 3d. Although the ratios at the three spatial frequencies were significantly different, $F(2, 27) = 17.7, p < .01$, the ratios at a given spatial frequency did not depend on the temporal frequency—regression analysis showed that the slope of each ratio curve was not significantly different from zero, $F(1, 58) = 0.26, p > .5$; $F(1, 48) = 1.00, p > .3$; and $F(1, 38) = 2.56, p > .1$, at low, intermediate, and high spatial frequencies, respectively. At low, intermediate, and high spatial frequencies, the average motion sensitivity ratios between the nonamblyopic eyes and the amblyopic eyes were $1.1 \pm 0.1, 2.7 \pm 0.5$, and 9.3 ± 1.4 , respectively.

The MTFs in moving grating detection also exhibited no significant difference between the NAEs and the CEs in all the three tested spatial frequencies (Figures 3e, 3f, and 3g), $F(1, 8) = 2.24, p > .1, F(1, 8) = 1.08, p > .3$, and $F(1, 8) = 1.15, p > .3$, in low, intermediate, and high spatial frequency conditions, respectively. At the low spatial frequency, the MTF of the AEs showed no significant loss compared to that of the nonamblyopic eyes, $F(1, 4) = 0.83, p > .4$, whereas significant loss appeared at the

		a_1	b_1	c_1	a_2	b_2	c_2
AE	CSF5	1.755	0.9225	14.27	1.375	3.887	1.787
	CSF10	1.842	0.7843	13.41	1.433	3.962	1.866
NAE	CSF5	2.142	0.6489	4.494	0.221	3.916	0.2646
	CSF10	2.125	0.6386	4.291	0.2431	3.877	0.2984
CE	CSF5	2.252	1.638	5.348	0.7147	3.999	2.358
	CSF9	2.082	0.7684	4.583	0.1808	3.819	0.9042

Table 3a. Parameters of the best fitting DOGs contrast sensitivity function (CSF).

		SF	Optimal TF (Hz)	a_1	b_1	c_1	a_2	b_2	c_2
AE	Detection	Low	10	1.825	2.915	5.639	0.8571	5.17	0.5832
		Mid	7	1.846	1.641	5.127	0.7255	5.1	0.5694
		High	4	1.114	1.214	3.97	0.2991	4.862	0.9165
	Discrimination	Low	10	1.984	2.493	4.789	0.7063	5.17	0.5074
		Mid	8	1.768	2.226	4.122	0.7076	5.16	0.554
		High	6	0.7651	2.392	3.724	0.3398	4.88	0.6865
NAE	Detection	Low	11	1.961	3.097	6.446	1.012	5.1	0.5719
		Mid	5	2.187	1.885	5.958	0.8828	5.12	0.5906
		High	5	1.846	1.322	5.383	0.677	5.14	0.7637
	Discrimination	Low	9	1.915	2.959	6.168	0.9384	5.17	0.5897
		Mid	8	2.249	1.902	4.503	0.6845	5.16	0.4872
		High	6	1.889	1.954	4.149	0.7046	5.17	0.663
CE	Detection	Low	11	1.992	3.24	7.632	0.976	5.15	0.5624
		Mid	7	2.228	1.853	6.617	0.8704	5.17	0.6127
		High	5	2.075	1.424	5.588	0.733	5.09	0.5571
	Discrimination	Low	9	2.042	2.492	5.11	0.6554	5.11	0.2522
		Mid	6	2.179	1.965	5.274	0.7483	5.17	0.494
		High	4	1.894	1.552	5.387	0.678	5.12	0.5466

Table 3b. Parameters of the best fitting DOGs (MTF) and the optimal temporal frequency in motion detection and motion direction discrimination. CSF5 in AE and NAE: average CSF of the five amblyopic subjects who attended all the series experiments. CSF10: average CSF of all the 10 amblyopic subjects. CSF5 in CE: average CSF of the five normal subjects who ran all the tests. CSF9 means average CSF of all the control subjects. SF: spatial frequency; TF: temporal frequency; AE: amblyopic eye; NAE: nonamblyopic eye; CE, control eye.

intermediate, $F(1, 4) = 8.03$, $p < .05$, and high spatial frequencies, $F(1, 4) = 12.6$, $p < .03$. The parameters of the best fitting DOGs to the MTFs are listed [Table 3b](#).

We also calculated the ratio of moving grating detection sensitivities between the nonamblyopic and the amblyopic eyes ([Figure 3h](#)). Again, the average ratios at the three spatial frequencies were significantly different, $F(2, 12) = 5.12$, $p < .03$, although, at a given spatial frequency, the ratios did not depend on the temporal frequency—regression analysis showed that the slope of each ratio curve was not significantly different from zero, $F(1, 28) = 0.90$, $p > .3$; $F(1, 23) = 0.21$, $p > .5$; and $F(1, 18) = 0.15$, $p > .5$, for the ratio functions at the three spatial frequencies. At low, intermediate, and high spatial frequencies, the average moving grating detection sensitivity ratios between the nonamblyopic eyes and the amblyopic eyes were 1.3 ± 0.3 , 2.3 ± 1.1 , and 6.9 ± 2.2 , respectively.

To test whether the observed local motion deficits were beyond the deficits in moving grating detection, we calculated the sensitivity ratio between the two tasks for each spatial and temporal frequency condition ([Figures 3i](#), [3j](#), and [3k](#)). In the amblyopic eyes, the sensitivity ratio between motion direction discrimination and moving grating detection was not significantly different across all the spatial, $F(2, 8) = 0.43$, $p > .5$, and temporal frequencies, $F(5, 20) = 0.37$, $p > .5$, and the average was only marginally different from 1.0, $t(74) = 1.73$, $p = .08$. The result suggests that the observed local motion deficits in the amblyopic eyes are only marginally greater than

their spatial vision deficits. Spatial vision deficits account for most of the apparent local motion deficits.

To be complete, we also calculated the sensitivity ratio between the motion direction discrimination and the moving grating detection tasks in the nonamblyopic eyes ([Figures 3i](#), [3j](#), and [3k](#)). The ratios were also not significantly different across spatial, $F(2, 8) = 1.69$, $p > .2$, and temporal frequencies, $F(5, 20) = 1.02$, $p > .4$, and the average was not significantly different from 1.0, $t(74) = 0.41$, $p > .5$.

Because of the large intersubject variance among amblyopes, it is necessary to evaluate the sensitivity ratio between motion direction discrimination and moving grating detection for all the individual observers. In [Figure 4](#), we plot the two sensitivities against each other for all the amblyopic observers across all the spatial and the temporal frequency conditions. In both the amblyopic ([Figure 4a](#)) and the nonamblyopic eyes ([Figure 4b](#)), most of the data points, except a few for subject H. H. X., are on or near the identity line suggesting that the individual data are largely consistent with the average results.

Because the sensitivity ratios between the nonamblyopic and the amblyopic eyes in both motion direction discrimination and moving grating detection were statistically independent of temporal frequencies, we computed the average sensitivity ratio at each spatial frequency for both tasks. These average ratios are plotted in [Figure 5a](#), along with the corresponding contrast sensitivity ratios from the CSF measurements. The ratio curves from the three tasks are not significantly different, $F(2, 8) = 1.53$,

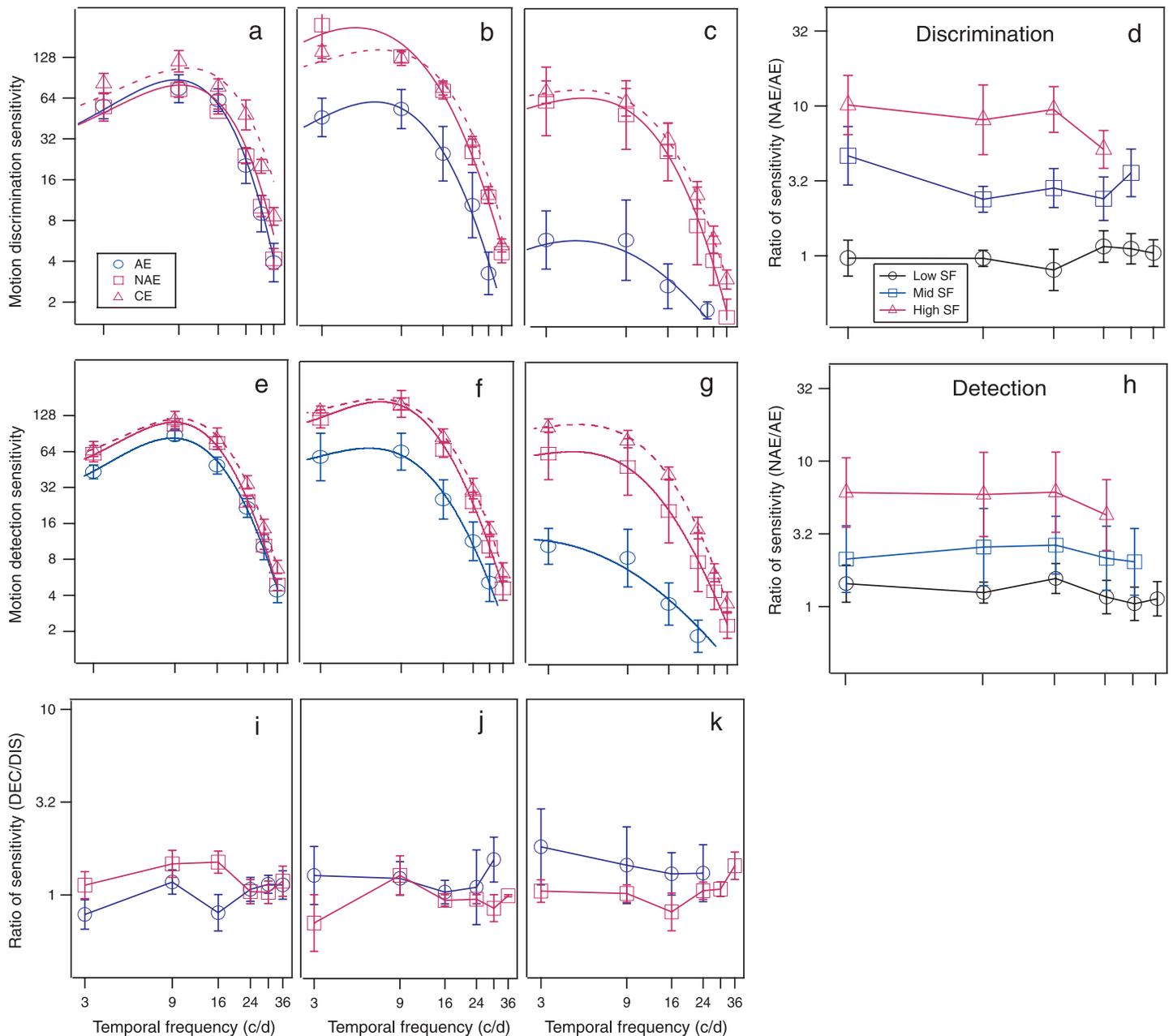


Figure 3. Data from the five amblyopes and five control subjects who participated in the tests. (a, b, c) Average motion direction discrimination modulation transfer functions (MTF) for the amblyopic eyes (AE), the nonamblyopic eyes (NAE), and the control eyes (CE). (d) Average motion direction discrimination sensitivity ratio between the nonamblyopic and the amblyopic eyes at the three spatial frequencies. (e, f, g) Average moving sine-wave detection MTFs. (h) Average moving sine-wave detection sensitivity ratio between the nonamblyopic and the amblyopic eyes. (i, j, k) Average motion direction discrimination versus moving sine-wave detection sensitivity ratio for AEs and NAEs. The error bars represent one standard error.

$p > .2$. This, together with the observation that the ratios in both motion direction discrimination and moving grating detection were statistically independent of temporal frequencies, suggests that the deficits in both motion direction discrimination and moving grating detection are quantitatively equivalent to the CSF deficits in the same spatial frequencies.

Motion direction discrimination versus contrast sensitivity

In the previous section, we showed that amblyopic deficits in both motion direction discrimination and moving grating detection were statistically independent

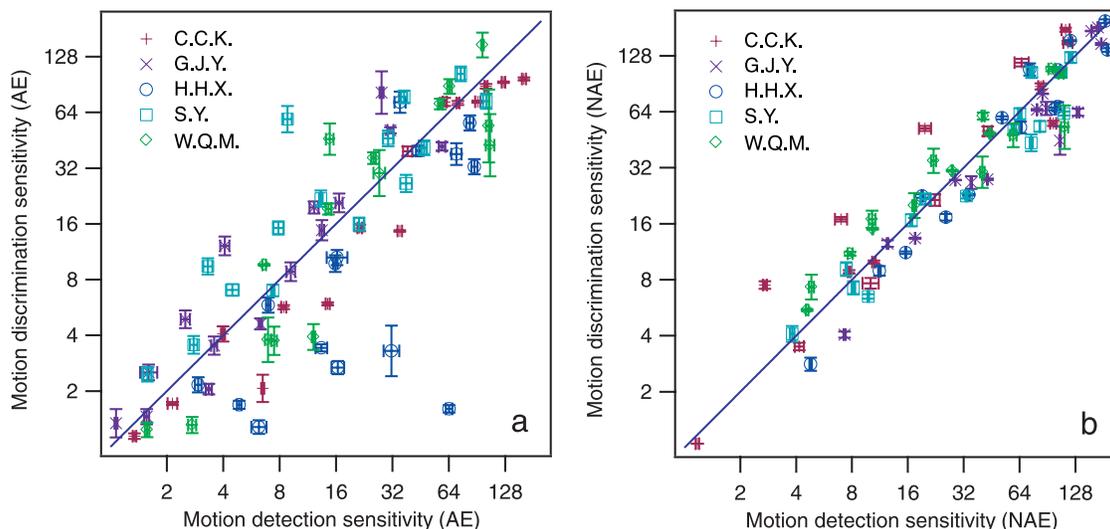


Figure 4. Scatter plots of motion direction discrimination sensitivity and moving sine-wave detection sensitivity in (a) the amblyopic eye and (b) the nonamblyopic eyes of the five amblyopic observers who completed all the tests. The error bars represent one standard error.

of temporal frequency. In this section, we focus on motion direction discrimination and compared deficits in motion direction discrimination to those in contrast sensitivity. We describe the results from all the 10 amblyopic subjects and 9 normal controls.

Figures 6a, 6b, and 6c depict the average MTFs for motion direction discrimination at three spatial frequencies, along with the predictions of the best fitting DOG models. At the low spatial frequency, The MTF of the amblyopic eyes showed no significant loss compared to that of the nonamblyopic eyes, $F(1, 9) = 0.11, p > .5$. The MTFs of the nonamblyopic eyes and the control eyes also showed no significant difference, $F(1, 17) = 3.00, p > .1$.

The peak sensitivity of AE, NAE, and CE all occurred around 9 Hz (Figure 6a). At the intermediate spatial frequency, the MTF of the amblyopic eyes became significantly different from that of the nonamblyopic eyes, $(1, 9) = 14.2, p < .01$, although the MTFs of the NAE and the CE still showed no significant differences, $F(1, 17) = 0.73, p > .4$. The peak sensitivity all appeared around 6 Hz (Figure 6b). At the high spatial frequency, the MTF of the amblyopic eyes was also significantly different from that of the nonamblyopic eyes, $F(1, 9) = 55.1, p < .01$, although the MTFs of the NAE and the CE were virtually the same, $F(1, 17) = 0.58, p > .4$. The peaks of all the MTFs occurred around 5 Hz (Figure 6c).

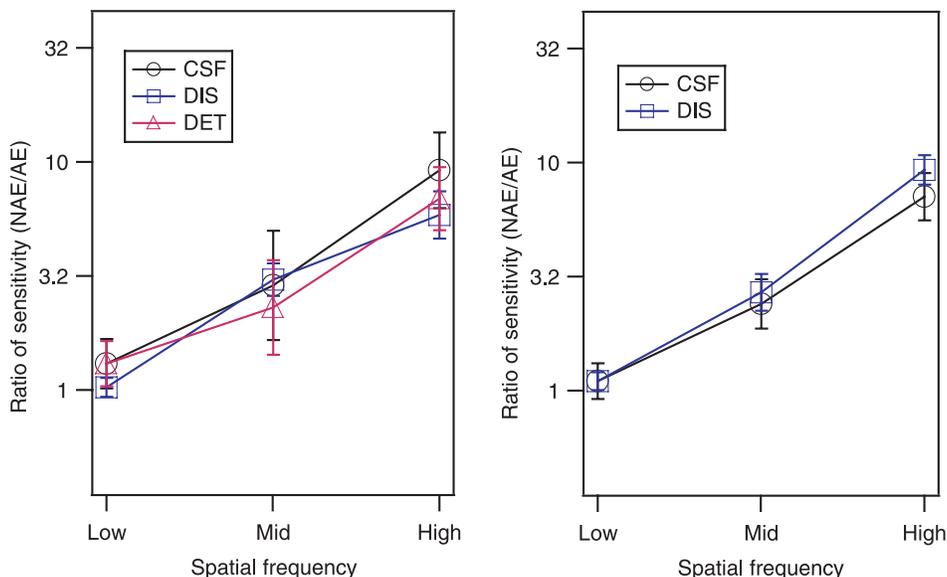


Figure 5. Average sensitivity ratio between NAE and AE in motion direction discrimination (squares), moving sine-wave detection (triangles), and contrast sensitivity (circles) in three spatial frequencies. (a) Data from the five amblyopes who completed all the tests. (b) Data from all the 10 amblyopes. The error bars represent one standard error.

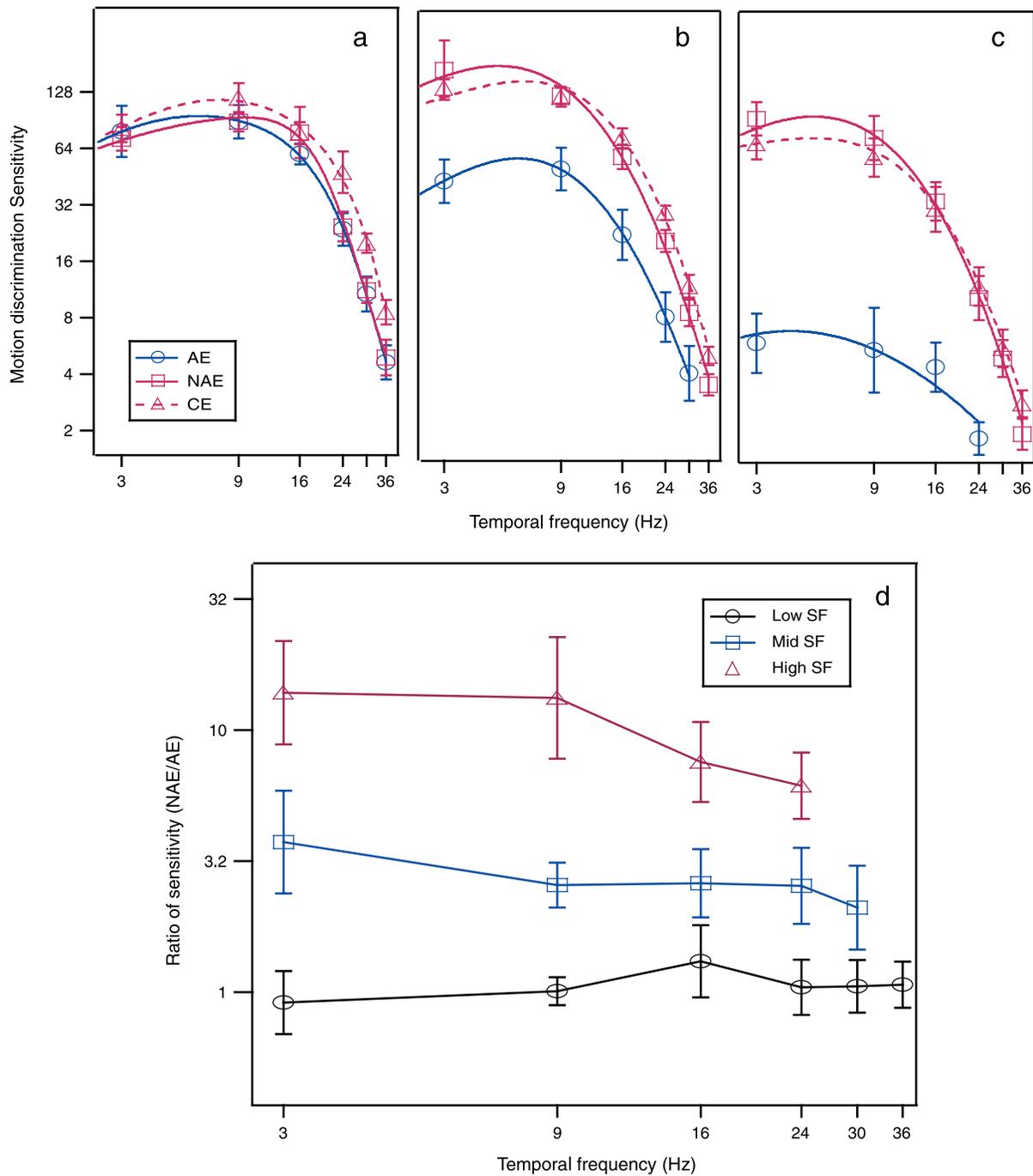


Figure 6. Modulation transfer functions of motion direction discrimination for the amblyopic eyes (AE), the nonamblyopic eyes (NAE), and the control eyes (CE) at the (a) low spatial frequency, (b) the intermediate spatial frequency, and (c) the high spatial frequency. Data from all the 10 amblyopic and 9 normal observers are included. The blue solid, red solid, and red dashed curves represent the predictions of the best fitting DOGs (circles: AE; squares: NAE; triangles: CE). (d) Average motion sensitivity ratio between the nonamblyopic and the amblyopic eyes at low (Low SF), intermediate (Mid SF), and high (High SF) spatial frequencies. The error bars represent one standard error.

In Figure 6d, we plot the motion discrimination sensitivity ratios of the nonamblyopic eyes to amblyopic eyes as functions of temporal frequency for all the three spatial frequencies. Although the ratios at the three spatial frequencies were significantly different, $F(2, 27) = 17.7, p < .01$, the ratios at a given

spatial frequency did not depend on the temporal frequency—regression analysis showed that the slope of each ratio curve was not significantly different from zero, $F(1, 58) = 0.26, p > .5$; $F(1, 48) = 1.00, p > .3$; and $F(1, 38) = 2.56, p > .1$, for the ratio functions at the three spatial frequencies. At low, intermediate, and high spatial

frequencies, the average motion sensitivity ratios between the nonamblyopic eyes and the amblyopic eyes were 1.1 ± 0.1 , 2.7 ± 0.5 , 9.3 ± 1.4 .

The average motion sensitivity ratios in the three spatial frequency conditions are plotted in [Figure 5b](#), along with the corresponding contrast sensitivity ratios obtained from the CSF measurements. The ratio curves from the motion direction discrimination and the CSF tasks are virtually identical, $F(1, 9) = 0.50$, $p > .4$, consistent with the hypothesis that the observed motion deficits can be accounted for by reduced contrast sensitivities.

Discussion

In this study, we evaluated (primarily) local motion perception deficits in anisometric amblyopia. We found that the apparent local motion deficits in anisometric amblyopia can be almost completely accounted for by deficits in moving grating detection. In addition, the differences between the amblyopic and the nonamblyopic eyes are nonspecific to temporal frequency in both motion direction discrimination and moving grating detection and are quantitatively identical to the differences in their contrast sensitivities. These results suggest that local motion-sensitive mechanisms are largely intact in anisometric amblyopia; the apparent local motion deficits can be modeled with deficits in CSFs.

Our results complements that of Hess and Anderson (1993), who found that, for strabismic amblyopia, the apparent deficits in local motion processing can be mostly accounted for by deficits in their ability to detect moving gratings except over a narrow part of the visible range in the amblyopic eyes. In fact, our results are completely consistent with that of the single anisometric amblyope in Hess and Anderson, who showed no motion deficit beyond spatial vision deficit in the entire range of tested conditions. Together with Hess and Anderson, our results strongly suggest that the reported global motion deficits in various types of amblyopia (Ellemberg et al., 2002; Kiorpes et al., 2006; Simmers et al., 2003) are mostly likely of extra-striate origin.

Extracting motion direction from moving sine-wave grating clearly involves integrating motion from a number of motion detectors that computes motion from local patches of the moving stimuli. Because, for moving sine-wave gratings, the motion signals in all the “local” patches are consistent, the current study is primarily concerned with local motion processing in amblyopia. In this regard, our results are highly related to Hess et al. (2006), who found that amblyopes have normal integration of local motion when the inputs to the higher level processes were equated between the normal and the amblyopic eyes. Although global motion perception might involve both a local motion and a global integration stage (Morrone

et al., 1995), Hess and Anderson (1993) and the current study suggest that in both strabismic and anisotropic amblyopia, there is virtually no local motion deficit beyond spatial vision loss. Once the visibility of the stimuli is equated, any additional global motion deficit must stem from deficits in global motion integration, a function performed in extra-striate cortical areas (Baker et al., 1991; Mikami et al., 1986a, 1986b; Newsome & Pare, 1988; Plant & Nakayama, 1993; Sunaert et al., 1999; Tootell et al., 1995; Vaina, 1989; Vaina et al., 2001).

The observation that deficits in both local motion direction discrimination and moving grating detection are independent of temporal frequency and can be largely accounted for by CSF deficits is also consistent with results in the highly related domain of temporal vision. Bradley and Freeman (1985) suggested that the presence or the absence of reduced sensitivity to flicker stimuli mainly depended on the spatial deficits in amblyopia. Manny and Levi (1982b) reported that the critical fusion frequency of the amblyopic eye was equal to that of the nonamblyopic eye or was only slightly reduced. In this study, we found that the peak of the temporal MTF in both motion direction discrimination and moving grating detection was virtually the same in the amblyopic and the nonamblyopic eyes ([Table 3b](#)). The observation that the average sensitivity ratios between the amblyopic and the nonamblyopic eyes were identical to their CSF ratios are consistent with the notion that the loss of spatiotemporal contrast sensitivity should be more related to spatial vision rather than temporal factors (Manny & Levi, 1982a; Rentschler, Hiltz, & Brettel, 1981).

Since the pioneering work of Campbell, Hess, Watson, and Banks (1978), perceptual learning has been evaluated as a potential therapy for amblyopia, although the results have been somewhat mixed (Ciuffreda, Goldner, & Connelly, 1980; Mehdorn, Mattheus, Schuppe, Klein, & Kommerell, 1981; Schor & Levi, 1980; Terrell, 1981). Using longer training periods and more demanding tasks, several recent studies (Chung, Li, & Levi, 2006; Levi & Polat, 1996; Levi, Polat, & Hu, 1997; Polat, Ma-Naim, Belkin, & Sagi, 2004; Zhou et al., 2006) found that perceptual learning can significantly improve spatial vision of adults with amblyopia. For example, Zhou et al. (2006) found that training in a simple sine-wave grating detection task significantly improved the contrast sensitivity and visual acuity of adult anisometric amblyopes. We predict, based on the conclusion of the current study, that training anisometric amblyopes in contrast detection would not only lead to improve contrast sensitivity but also improve local motion perception.

Acknowledgments

This research was supported by the National Natural Science Foundation of China (grants 30128006 and

30630027), the National Basic Research Program (2006CB500804), the Foundation of Chinese Academy of Sciences (grants KGCX2-SW-101), the State Key Laboratory of Brain and Cognitive Science, Institute of Biophysics, Chinese Academy of Sciences, and the US National Eye Institute.

Commercial relationships: none.

Corresponding authors: Zhong-Lin Lu and Yifeng Zhou
Email: zhonglin@usc.edu.

Address: Department of Psychology, SGM 501, University of Southern California, Los Angeles, CA 90089-1061; and School of Life Science, University of Science and Technology of China, Hefei, Anhui 230027, P. R. China.

Footnote

¹The log approximately equates the standard error over large ranges in contrast thresholds, corresponding to weight least squares, and equivalent to the maximum likelihood solution for continuous data.

References

- Anderson, S. J., Holliday, I. E., & Harding, G. F. (1999). Assessment of cortical dysfunction in human strabismic amblyopia using magnetoencephalography (MEG). *Vision Research*, *39*, 1723–1738. [PubMed]
- Asper, L., Crewther, D., & Crewther, S. G. (2000). Strabismic amblyopia: Part 1. Psychophysics. *Clinical and Experimental Optometry*, *83*, 49–58. [PubMed]
- Baker, C. L., Jr., Hess, R. F., & Zihl, J. (1991). Residual motion perception in a “motion-blind” patient, assessed with limited-lifetime random dot stimuli. *Journal of Neuroscience*, *11*, 454–461. [PubMed] [Article]
- Barnes, G. R., Hess, R. F., Dumoulin, S. O., Achtman, R. L., & Pike, G. B. (2001). The cortical deficit in humans with strabismic amblyopia. *The Journal of Physiology*, *533*, 281–297. [PubMed] [Article]
- Bonhomme, G. R., Liu, G. T., Miki, A., Francis, E., Dobre, M. C., Modestino, E. J., et al. (2006). Decreased cortical activation in response to a motion stimulus in anisometric amblyopic eyes using functional magnetic resonance imaging. *Journal of American Association for Pediatric Ophthalmology and Strabismus*, *10*, 540–546. [PubMed]
- Bradley, A., & Freeman, R. D. (1981). Contrast sensitivity in anisometric amblyopia. *Investigative Ophthalmology & Visual Science*, *21*, 467–476. [PubMed] [Article]
- Bradley, A., & Freeman, R. D. (1985). Temporal sensitivity in amblyopia: An explanation of conflicting reports. *Vision Research*, *25*, 39–46. [PubMed]
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436. [PubMed]
- Campbell, F. W., Hess, R. F., Watson, P. G., & Banks, R. (1978). Preliminary results of a physiologically based treatment of amblyopia. *British Journal of Ophthalmology*, *62*, 748–755. [PubMed] [Article]
- Chung, S. T., Li, R. W., & Levi, D. M. (2006). Identification of contrast-defined letters benefits from perceptual learning in adults with amblyopia. *Vision Research*, *46*, 3853–3861. [PubMed]
- Ciuffreda, K. J., Goldner, K., & Connelly, R. (1980). Lack of positive results of a physiologically based treatment of amblyopia. *British Journal of Ophthalmology*, *64*, 607–612. [PubMed] [Article]
- Ciuffreda, K. J., Levi, D. M., & Selenow, A. (1991). *Amblyopia: Basic and clinical aspects*. Boston: Butterworth-Heinemann.
- Daw, N. W. (1998). Critical periods and amblyopia. *Archives of Ophthalmology*, *116*, 502–505. [PubMed] [Article]
- DeLint, P. J., Berendschot, T. T., & van Norren, D. (1998). A comparison of the optical Stiles–Crawford effect and retinal densitometry in a clinical setting. *Investigative Ophthalmology & Visual Science*, *39*, 1519–1523. [PubMed] [Article]
- Elleberg, D., Lewis, T. L., Maurer, D., Brar, S., & Brent, H. P. (2002). Better perception of global motion after monocular than after binocular deprivation. *Vision Research*, *42*, 169–179. [PubMed]
- Hendrickson, A. E., Movshon, J. A., Eggers, H. M., Gizzi, M. S., Boothe, R. G., & Kiorpes, L. (1987). Effects of early unilateral blur on the macaque’s visual system: II. Anatomical observations. *Journal of Neuroscience*, *7*, 1327–1339. [PubMed] [Article]
- Hess, R. F., & Anderson, S. J. (1993). Motion sensitivity and spatial undersampling in amblyopia. *Vision Research*, *33*, 881–896. [PubMed]
- Hess, R. F., & Demanins, R. (1998). Contour integration in anisometric amblyopia. *Vision Research*, *38*, 889–894. [PubMed]
- Hess, R. F., Demanins, R., & Bex, P. J. (1997). A reduced motion aftereffect in strabismic amblyopia. *Vision Research*, *37*, 1303–1311. [PubMed]
- Hess, R. F., & Howell, E. R. (1977). The threshold contrast sensitivity function in strabismic amblyopia: Evidence for a two type classification. *Vision Research*, *17*, 1049–1055. [PubMed]
- Hess, R. F., Mansouri, B., Dakin, S. C., & Allen, H. A. (2006). Integration of local motion is normal in

- amblyopia. *Journal of the Optical Society of America A, Optics, image science, and vision*, *23*, 986–992. [[PubMed](#)]
- Howell, E. R., Mitchell, D. E., & Keith, C. G. (1983). Contrast thresholds for sine gratings of children with amblyopia. *Investigative Ophthalmology & Visual Science*, *24*, 782–787. [[PubMed](#)] [[Article](#)]
- Kiorpes, L., Kiper, D. C., O’Keefe, L. P., Cavanaugh, J. R., & Movshon, J. A. (1998). Neuronal correlates of amblyopia in the visual cortex of macaque monkeys with experimental strabismus and anisometropia. *Journal of Neuroscience*, *18*, 6411–6424. [[PubMed](#)] [[Article](#)]
- Kiorpes, L., & McKee, S. P. (1999). Neural mechanisms underlying amblyopia. *Current Opinion in Neurobiology*, *9*, 480–486. [[PubMed](#)]
- Kiorpes, L., Tang, C., & Movshon, J. A. (2006). Sensitivity to visual motion in amblyopic macaque monkeys. *Visual Neuroscience*, *23*, 247–256. [[PubMed](#)]
- Kovács, I., Polat, U., Pennefather, P. M., Chandna, A., & Norcia, A. M. (2000). A new test of contour integration deficits in patients with a history of disrupted binocular experience during visual development. *Vision Research*, *40*, 1775–1783. [[PubMed](#)]
- Kozma, P., & Kiorpes, L. (2003). Contour integration in amblyopic monkeys. *Visual Neuroscience*, *20*, 577–588. [[PubMed](#)]
- Kubová, Z., Kuba, M., Juran, J., & Blakemore, C. (1996). Is the motion system relatively spared in amblyopia? Evidence from cortical evoked responses. *Vision Research*, *36*, 181–190. [[PubMed](#)]
- Levi, D. M., & Klein, S. (1982). Differences in Vernier discrimination for grating between strabismic and anisometropic amblyopes. *Investigative Ophthalmology & Visual Science*, *23*, 398–407. [[PubMed](#)] [[Article](#)]
- Levi, D. M., Klein, S. A., & Sharma, V. (1999). Position jitter and undersampling in pattern perception. *Vision Research*, *39*, 445–465. [[PubMed](#)]
- Levi, D. M., & Polat, U. (1996). Neural plasticity in adults with amblyopia. *Proceedings of the National Academy of Sciences of the United States of America*, *93*, 6830–6834. [[PubMed](#)] [[Article](#)]
- Levi, D. M., Polat, U., & Hu, Y. S. (1997). Improvement in Vernier acuity in adults with amblyopia. Practice makes better. *Investigative Ophthalmology & Visual Science*, *38*, 1493–1510. [[PubMed](#)] [[Article](#)]
- Levitt, H. (1971). Transformed up–down methods in psychoacoustics. *Journal of the Acoustical Society of America*, *49*, 467. [[PubMed](#)]
- Li, X., Lu, Z. L., Xu, P., Jin, J., & Zhou, Y. (2003). Generating high gray-level resolution monochrome displays with conventional computer graphics cards and color monitors. *Journal of Neuroscience Methods*, *130*, 9–18. [[PubMed](#)]
- Manny, R. E., & Levi, D. M. (1982a). Psychophysical investigations of the temporal modulation sensitivity function in amblyopia: Spatiotemporal interactions. *Investigative Ophthalmology & Visual Science*, *22*, 525–534. [[PubMed](#)] [[Article](#)]
- Manny, R. E., & Levi, D. M. (1982b). Psychophysical investigations of the temporal modulation sensitivity function in amblyopia: Uniform field flicker. *Investigative Ophthalmology & Visual Science*, *22*, 515–524. [[PubMed](#)] [[Article](#)]
- Mansouri, B., Allen, H. A., & Hess, R. F. (2005). Detection, discrimination and integration of second-order orientation information in strabismic and anisometropic amblyopia. *Vision Research*, *45*, 2449–2460. [[PubMed](#)]
- Mehdorn, E., Mattheus, S., Schuppe, A., Klein, U., & Kommerell, G. (1981). Treatment for amblyopia with rotating gratings and subsequent occlusion: A controlled study. *International Ophthalmology*, *3*, 161–166. [[PubMed](#)]
- Mikami, A., Newsome, W. T., & Wurtz, R. H. (1986a). Motion selectivity in macaque visual cortex: I. Mechanisms of direction and speed selectivity in extrastriate area MT. *Journal of Neurophysiology*, *55*, 1308–1327. [[PubMed](#)]
- Mikami, A., Newsome, W. T., & Wurtz, R. H. (1986b). Motion selectivity in macaque visual cortex: II. Spatiotemporal range of directional interactions in MT and V1. *Journal of Neurophysiology*, *55*, 1328–1339. [[PubMed](#)]
- Morrone, M. C., Burr, D. C., & Vaina, L. M. (1995). Two stages of visual processing for radial and circular motion. *Nature*, *376*, 507–509. [[PubMed](#)]
- Movshon, J. A., Eggers, H. M., Gizzi, M. S., Hendrickson, A. E., Kiorpes, L., & Boothe, R. G. (1987). Effects of early unilateral blur on the macaque’s visual system: III. Physiological observations. *Journal of Neuroscience*, *7*, 1340–1351. [[PubMed](#)] [[Article](#)]
- Newsome, W. T., & Pare, E. B. (1988). A selective impairment of motion perception following lesions of the middle temporal visual area (MT). *Journal of Neuroscience*, *8*, 2201–2211. [[PubMed](#)] [[Article](#)]
- Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442. [[PubMed](#)]
- Plant, G. T., & Nakayama, K. (1993). The characteristics of residual motion perception in the hemifield

- contralateral to lateral occipital lesions in humans. *Brain*, *116*, 1337–1353. [[PubMed](#)]
- Polat, U., Ma-Naim, T., Belkin, M., & Sagi, D. (2004). Improving vision in adult amblyopia by perceptual learning. *Proceedings of the National Academy of Sciences of the United States of America*, *101*, 6692–6697. [[PubMed](#)] [[Article](#)]
- Popple, A. V., & Levi, D. M. (2000). Amblyopes see true alignment where normal observers see illusory tilt. *Proceedings of the National Academy of Sciences of the United States of America*, *97*, 11667–11672. [[PubMed](#)] [[Article](#)]
- Rentschler, I., Hilz, R., & Brettel, H. (1981). Amblyopic abnormality involves neural mechanisms concerned with movement processing. *Investigative Ophthalmology & Visual Science*, *20*, 695–700. [[PubMed](#)] [[Article](#)]
- Rohaly, A. M., & Buchsbaum, G. (1988). Inference of global spatiochromatic mechanisms from contrast sensitivity functions. *Journal of the Optical Society of America A, Optics and image science*, *5*, 572–576. [[PubMed](#)]
- Rohaly, A. M., & Buchsbaum, G. (1989). Global spatiochromatic mechanism accounting for luminance variations in contrast sensitivity functions. *Journal of the Optical Society of America A, Optics and image science*, *6*, 312–317. [[PubMed](#)]
- Schor, C. M., & Levi, D. M. (1980). Direction selectivity for perceived motion in strabismic and anisometric amblyopia. *Investigative Ophthalmology & Visual Science*, *19*, 1094–1104. [[PubMed](#)] [[Article](#)]
- Schroder, J. H., Fries, P., Roelfsema, P. R., Singer, W., & Engel, A. K. (2002). Ocular dominance in extrastriate cortex of strabismic amblyopic cats. *Vision Research*, *42*, 29–39. [[PubMed](#)]
- Sharma, V., Levi, D. M., & Klein, S. A. (2000). Undercounting features and missing features: Evidence for a high-level deficit in strabismic amblyopia. *Nature Neuroscience*, *3*, 496–501. [[PubMed](#)] [[Article](#)]
- Simmers, A. J., Ledgeway, T., & Hess, R. F. (2005). The influences of visibility and anomalous integration processes on the perception of global spatial form versus motion in human amblyopia. *Vision Research*, *45*, 449–460. [[PubMed](#)]
- Simmers, A. J., Ledgeway, T., Hess, R. F., & McGraw, P. V. (2003). Deficits to global motion processing in human amblyopia. *Vision Research*, *43*, 729–738. [[PubMed](#)]
- Sunaert, S., Van Hecke, P., Marchal, G., & Orban, G. A. (1999). Motion-responsive regions of the human brain. *Experimental Brain Research*, *127*(4), 355–370. [[PubMed](#)]
- Terrell, A. (1981). Cambridge stimulator treatment for amblyopia. An evaluation of 80 consecutive cases treated by this method. *Australian Journal of Ophthalmology*, *9*, 121–127. [[PubMed](#)]
- Tootell, R. B., Reppas, J. B., Kwong, K. K., Malach, R., Born, R. T., Brady, T. J., et al. (1995). Functional analysis of human MT and related visual cortical areas using magnetic resonance imaging. *Journal of Neuroscience*, *15*, 3215–3230. [[PubMed](#)] [[Article](#)]
- Vaina, L. M. (1989). Selective impairment of visual motion interpretation following lesions of the right occipito-parietal area in humans. *Biological Cybernetics*, *61*, 347–359. [[PubMed](#)]
- Vaina, L. M., Cowey, A., Eskew, R. T., LeMay, M., & Kemper, T. (2001). Regional cerebral correlates of global motion perception: Evidence from unilateral cerebral brain damage. *Brain*, *124*, 310–321. [[PubMed](#)] [[Article](#)]
- Wong, E. H., Levi, D. M., & McGraw, P. V. (2001). Is second-order spatial loss in amblyopia explained by the loss of first-order spatial input? *Vision Research*, *41*, 2951–2960. [[PubMed](#)]
- Xu, P., Lu, Z. L., Qiu, Z., & Zhou, Y. (2006). Identify mechanisms of amblyopia in Gabor orientation identification with external noise. *Vision Research*, *46*, 3748–3760. [[PubMed](#)]
- Zhou, Y., Huang, C., Xu, P., Tao, L., Qiu, Z., Li, X., et al. (2006). Perceptual learning improves contrast sensitivity and visual acuity in adults with anisometric amblyopia. *Vision Research*, *46*, 739–750. [[PubMed](#)]