Factors limiting contrast sensitivity in experimentally amblyopic macaque monkeys

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Abstract

Contrast detection is impaired in amblyopes. To understand the contrast processing deficit in amblyopia, we studied the effects of masking noise on contrast threshold in amblyopic macaque monkeys. Amblyopia developed as a result of either experimentally induced strabismus or anisometropia. We used random spatiotemporal broadband noise of varying contrast power to mask the detection of sinusoidal grating patches. We compared masking in the amblyopic and non-amblyopic eyes. From the masking functions, we calculated equivalent noise contrast (the noise power at which detection threshold was elevated by $\sqrt{2}$) and signal-to-noise ratio (the ratio of threshold contrast to noise contrast at high noise power). The relation between contrast threshold and masking noise level was similar for amblyopic and non-amblyopic eyes. Although in most cases there was some elevation in equivalent noise for amblyopic compared to fellow eyes, signal-to-noise ratio showed greater variation with the extent of amblyopia. These results support the idea that the contrast detection deficit in amblyopia is a cortical deficit. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Amblyopia is a developmental disorder of vision, which is most commonly identified by a loss of visual acuity in one eye. Amblyopia often occurs in association with strabismus and/or anisometropia. There have been many investigations into the psychophysical deficits shown by amblyopes. One consistent finding is that they reliably show deficits in contrast sensitivity throughout the middle and high spatial frequency range. It is therefore important to understand the source of the limitations on contrast detection in amblyopia.

Noise masking paradigms have been used to investigate the mechanisms underlying detection performance. Barlow (1977), Pelli (1981, 1990), and others (e.g. Burgess, Wagner, Jennings & Barlow, 1981; Kersten, 1984) have shown that, under certain assumptions, the limitations on contrast detection in the presence of masking noise of varying contrast power can be partitioned into additive and non-additive components. In this scheme, overall visual efficiency (that is, the fidelity with which we detect signals in noise) results from the combined action of two stages: an input stage, where noise acts additively and which is relatively peripheral in the system, and other later elements, where noise acts non-additively and which are relatively central. The level of internal input noise can be estimated by identifying the contrast at which increasing the power of external noise begins to elevate detection threshold. The performance of the central elements can be estimated from the ratio of signal to noise at contrast threshold when the noise contrast is high. We have adopted this framework to try to understand the poor contrast sensitivity of amblyopes.

Previous studies of the effect of masking in amblyopes have either used one-dimensional noise (Holopigian & Blake, 1984; Kersten, Hess & Plant, 1988) or a fixed-contrast masking stimulus (Nordmann, Freeman & Casanova, 1992). Nordmann et al. (1992)

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showed that the effect of a fixed masking noise of relatively low contrast power was similar in amblyopic and non-amblyopic eyes for both strabismic and anisometropic human observers, but did not explore the effect of varying noise contrast. In a recent study, Levi, Pelli and Chung (in preparation) used a letter identification task to study efficiency in amblyopes. They found reduced efficiency, here defined as poor identification performance at high noise contrasts, particularly for stimuli that were defined by high spatial frequencies.

Our goal in this study was to identify the underlying site of the amblyopic deficit by comparing the relative effects of masking noise on amblyopic and non-amblyopic eyes. We have used this approach to understand the relatively poor contrast sensitivity of infants and the limitations on their contrast sensitivity development (Kiorpes & Movshon, 1998). That study suggested that there was an additive noise limitation on contrast sensitivity in infants at low spatial frequencies, but that there was an additional component reflecting non-additive contributions at high spatial frequencies. Thus, in the Pelli (1990) scheme, contrast sensitivity has an important peripheral limit in infants. However, it is an open question just what mechanism, or level of the visual system, represents peripheral, or central, processing in this case. Peripheral limitations, in the ideal observer formulation (Pelli, 1990, 1991), were associated with the input stages of the system; central could be at any level beyond that. We suspect that the division between 'peripheral' and 'central' in this sense may in fact be more 'central' than has been supposed; we will return to this issue in Section 4.

Since amblyopes and infants both have relatively poor contrast sensitivity compared with normal adults, and numerous studies have suggested that amblyopic vision is similar to that in infants (Kiorpes, 1992; Levi & Carkeet, 1993), we wondered if the limitations on contrast sensitivity as determined by noise masking might be similar in infants and amblyopes. In the present study, the outcome was similar to what we found in infants in that the data show evidence of both additive and non-additive limitations on the performance of amblyopic eyes. However, unlike normal infants, the predominant deficit in the case of amblyopes appears to be central. Some of these data have been briefly presented previously (Kiorpes, Tang & Movshon, 1996, 1998).

2. Methods

2.1. Subjects

Thirteen experimentally amblyopic, *Macaca nemestrina* monkeys were subjects in this study. All animals were born at the Washington Regional Primate Research Center, and were hand-reared in the Visual Neuroscience Laboratory at New York University. All animal care conformed to guidelines approved by the New York University IACUC and the NIH Guide for Care and Use of Laboratory Animals. The animals ranged in age from 6 months to 8 years at the time of testing. Their visual environment was a normal laboratory environment, which was enriched with a wide variety of appropriate visual and tactile stimuli. The animals were also given daily opportunities for interaction with other monkeys and humans.

2.2. Experimental amblyopia

Amblyopia developed following either early induced strabismus or simulated anisometropia. Experimental strabismus, esotropia, was induced 20–30 days after birth in eight monkeys by one of two methods (see Kiorpes, Carlson & Alfi, 1989; Kiorpes, Kiper & Movshon, 1993; Kiorpes & Wallman, 1995). Surgical esotropia was created in six monkeys by transection of the left lateral rectus muscle; the left medial rectus muscle was resected and advanced to the limbus. Surgery was carried out under ketamine hydrochloride sedation using sterile surgical techniques. Toxin strabismus was created in two monkeys by injection of *Clostridium botulinum A* neurotoxin in the left lateral rectus muscle under ketamine hydrochloride sedation with EMG guidance. The resulting esotropia with both methods was typically moderate, ranging from 10 to 25 prism diopters, but was larger, about 35 prism diopters, in two cases. The deviation angle was estimated by the Hirschberg method from photographs; this method is accurate to about 5 prism diopters (see Kiorpes et al., 1989, for details). Experimental anisometropia was simulated in five monkeys by inserting a −10D extended-wear soft contact lens in the right eye and a zero-power lens in the left (Kiorpes et al., 1993). The monkeys wore the lenses beginning 10–25 days after birth, for a period of 7–10 months. The status and condition of the lenses was checked frequently throughout each day; missing lenses were infrequent, but were replaced immediately. The lenses were routinely changed and cleaned weekly. Regular ophthalmic examinations were performed to insure the health of the eyes. Eye alignment was evaluated casually, by inspection, daily and by the photographic Hirschberg method once during rearing. No strabismus was obvious during the rearing period or thereafter in any of these lens-reared animals, however, we would not have detected a tropia or phoria of less than 5 prism diopters.

Refractive errors were evaluated during rearing in all subjects. For refraction, each eye was dilated with one to three drops of 2.5% phenylephrine hydrochloride and three drops of 0.5 or 1% cyclopentolate. The strabismic monkeys were each refracted at least twice

within the first postnatal year; the lens-reared monkeys were refracted monthly. All refractions were performed by the same pediatric ophthalmologist. All monkeys had essentially equal refractive errors in the two eyes during early infancy. Two strabismic monkeys developed anisometropia of greater than 2 diopters during the first postnatal year and thus may be considered compound amblyopes. Two additional strabismic amblyopes developed anisometropia after the first postnatal year. Three of the five lens-reared monkeys developed anisometropia of greater than 2 diopters during the lens-rearing period; two additional lens-reared monkeys developed anisometropia after the lenses were removed. Rearing histories and refractive errors, measured closest to the age at test, are presented in Table 1. Also presented in the table is a dimensionless amblyopia index which is a measure of the depth of amblyopia. The amblyopia index is calculated by taking the area between the fitted contrast sensitivity function for the treated eye and the function for the untreated eye and dividing it by the area under the untreated eye's function. The index ranges from 0 (no deficit) to 1 (no measurable contrast sensitivity for the treated eye) and captures deficits in both contrast sensitivity and spatial resolution (see Kiorpes, Kiper, O'Keefe, Cavanaugh & Movshon, 1998).

2.3. Stimuli

Stimuli were presented on a Nanao T660i monitor which had a mean luminance of 56 cd m^{-2}. The display subtended 36° at 60 cm, which was the viewing distance used for deep amblyopes. Milder amblyopes and fellow eyes were tested at a distance of 120 cm. Stimulus presentation was controlled by a computer via an ATVista graphics board (Truevision). We used patches of vertical sinusoidal grating vignetted by a 2D spatial Gaussian, whose contrast was ramped on over 200 ms. Grating spatial frequency ranged from 0.5 to 4.0 c/deg. The standard deviation of the spatial Gaussian was 3° (except at the lowest spatial frequency, where the standard deviation was increased to insure presentation of at least 3 cycles of the grating). Once the grating reached full contrast (after the 200 ms ramp, which was accompanied by a tone), the animal was free to respond. Since the animals were freely viewing, the viewing duration was not controlled precisely. However, we measured response latencies for performance using each eye in strabismic and anisometropic amblyopes. Latencies ranged from 500 to 1000 ms and did not differ for amblyopic and non-amblyopic eyes for stimuli of comparable effective contrast.

The grating patches were presented alone and in the presence of random spatiotemporal broadband noise consisting of square pixels. The noise was refreshed with a new random noise field at a rate of 53 Hz and was interleaved on alternate frames with the grating. The noise was continuously present and filled the entire display. Noise pixel size was 11.6'. Noise Michelson contrast ranged from 0.01 to 0.50; the luminance distribution of pixel values was always binary. The details of the algorithm used for noise generation can be found in Gegenfurtner and Kiper (1992).

Table 1
Treatment history, refractive errors, and depth of amblyopia, as measured nearest the age at test, for each subject[a]

Monkey	Treatment	Onset age (days)	Age at test (years)	Amblyopia index	Spherical equivalent refractive error	
					Fellow eye	Treated eye
AN	TS	31	8.7	0.880	+7.0	+11.625
JS	TS	26	8	0.885	+1.625	+7.0
TX	SS	26	1.8	0.731	+2.25	+6.375[c]
WW	SS[b]	31	1.2	0.144	+1.25	+1.25
HF	SS	25	1.6	0.747	plano	+0.25
HN	SS	27	1.3	0.808	plano	+3.50[c]
HR	SS	21	1.0	0.755	+0.75	+2.50
HU	SS	17	1.1	0.960	+0.75	+1.25
CY	Lens	25	0.9	0.767	+0.375	+7.50[d]
CM	Lens	20	0.9	0.396	−0.50	+7.25[d]
DG	Lens	23	1.2	0.654	+1.00	+2.25
HK	Lens	24	0.8	0.242	+1.635	+6.50[d]
IR	Lens	24	0.8	0.461	+2.75	+5.125

[a] Amblyopia index reflects the depth of amblyopia which is derived from the contrast sensitivity functions and reflects deficits in contrast sensitivity as well as spatial resolution (see text). SS, surgical strabismus; TS, neurotoxin strabismus.
[b] Alternating fixation pattern.
[c] Greater than 2 diopters anisometropia detected during first 9 months after birth.
[d] Greater than 2 diopters anisometropia detected during lens rearing.

2.4. Behavioral methods

On each trial, a grating patch was presented on either the left or right side of the video display, 10° from center. The monkey's task was a spatial two-alternative forced-choice; she indicated on which side of the display the grating patch had appeared. The animals were trained to pull one of a pair of grab bars located on the front of the cage to indicate the side of stimulus presentation. They viewed the display monocularly, through natural pupils; optical correction was provided as needed during testing (see Kiorpes & Boothe, 1984). Correct responses were rewarded with apple juice; errors were signaled by a tone. Further details of these procedures may be found in earlier reports (Kiorpes et al., 1993; Kiorpes & Kiper, 1996; Kiorpes & Movshon, 1998).

Contrast threshold for each stimulus condition was established using method of constant stimuli. Each threshold was based on at least 200 trials; we collected 50–100 trials at each of three to five contrast levels chosen to span the performance range from 50 to 100% correct. Contrast threshold for each test spatial frequency was measured in the absence of noise and in the presence of each of a series of noise masks, up to the highest noise contrast (0.50). Data collection was counterbalanced across noise contrast level. Threshold estimates and standard errors were calculated using Probit analysis (Finney, 1971) of the log-transformed data sets.

Since grating detection is mediated by mechanisms that are selective for both spatial and temporal frequency, the contrast C of the noise is not actually the appropriate measure of its strength. The strength of the noise is best given in units of spectral density, or contrast power per unit bandwidth, which is the expected contrast power of a sample of the noise in a unit interval of spatiotemporal frequency. We calculated the spectral density of the noise for the binary noise conditions used throughout this study. The relationship between noise contrast and spectral density is shown by comparing the upper and lower abscissas in Fig. 1A. The upper abscissa shows the spectral density of the noise; the lower abscissa shows the corresponding noise contrast.

The sample data in Fig. 1A illustrate the variation in contrast threshold with the strength of the masking noise for one eye of an amblyopic monkey; the isolated point on the left side of the plot indicates the measured contrast threshold in the absence of noise (unmasked contrast threshold). The smooth curve represents the expected form of the masking function (Pelli, 1990), and from it we can infer two values that relate to the two proposed stages of contrast detection. The first is 'equivalent intrinsic noise', which is an estimate of the intrinsic noise associated with the input stages of the

visual system and is an additive factor; the second is the 'signal-to-noise ratio', which is an estimate of the efficiency of detection in high levels of external noise and is a non-additive factor. As illustrated in Fig. 1A, at low levels of external stimulus noise, threshold is little affected and the function is flat. This is the range over which intrinsic noise exceeds stimulus noise. At higher noise levels, threshold rises in proportion to noise contrast and the function has a slope of 1. This behavior is well known and is described by the relationship

$$C = R_{sn}\sqrt{N^2 + N_{eq}^2} \qquad (1)$$

where C is contrast threshold, R_{sn} is signal-to-noise ratio, N is the contrast of the masking noise, and N_{eq} is the equivalent intrinsic noise, referenced back to the visual scene in units equivalent to the masking noise contrast. When $N = N_{eq}$, contrast threshold is elevated by $\sqrt{2}$; this point is indicated by the arrow on the abscissa. For the remainder of the paper, we will give noise strength in units related to noise contrast rather than the spectral density of the noise, since these units are more intuitive for most readers. For values given in contrast units we will use the terms N_C and N_{eqC} in place of N and N_{eq}. The constant R_{sn} corresponds to the asymptotic signal to noise ratio at threshold, i.e. the vertical position of the masking function at high noise contrast.

3. Results

Amblyopes typically have elevated contrast thresholds for one eye, so we expect a difference in unmasked contrast threshold between the eyes, particularly at high spatial frequencies. We also expect that there might be differences in the masking functions for the two eyes. For example, the form of the masking function may be aberrant for the amblyopic eye, or the functions for the two eyes may be shifted with respect to one another. Two extreme possibilities for such shifts are illustrated in Fig. 1B and C. The pattern in Fig. 1B, a diagonal shift of the curve, would obtain if the amblyopic eye had higher equivalent intrinsic noise but had no deficit once the greater internal noise level was overcome by high-contrast masking noise. This pattern would reflect an additive, or peripheral (in the Pelli, 1990, scheme), limit on performance and would be characterized by variation in N_{eqC} but constant R_{sn}. The pattern in Fig. 1C, a vertical shift of the curve, would reflect a non-additive, or central, limit on performance and would be characterized by variation in R_{sn} but constant N_{eqC}.

The effects of masking noise were different for the two eyes of the amblyopic monkeys. However, the form of the masking function for the amblyopic eye was in general not different from that of the fellow eye; both
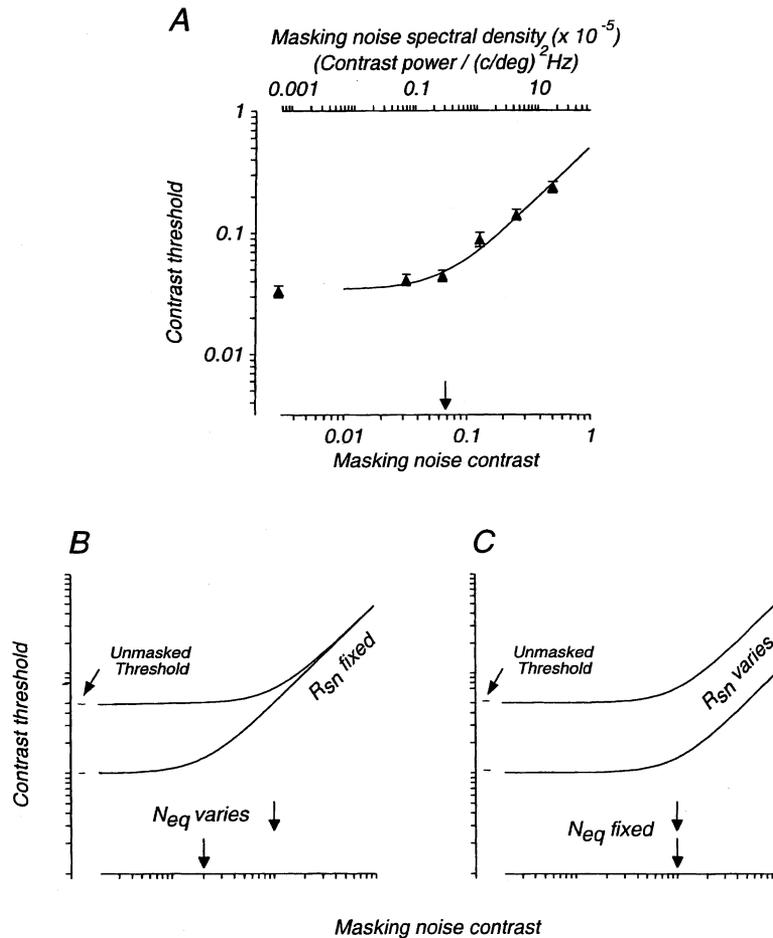
Fig. 1. (A) Example data showing the variation in contrast threshold with the strength of masking noise. Masking noise contrast is shown on the lower abscissa and the translation to noise spectral density is shown on the upper abscissa. Data are shown for one eye of one monkey (HF, amblyopic eye); the isolated point to the left is her unmasked (no noise) threshold for this spatial frequency (4 c/deg). The filled arrow points to the equivalent noise contrast for this data set. (B) The illustrated pattern of shift of the masking function for eyes that differ in contrast threshold would result from a difference in equivalent noise for the two eyes. The pair of arrows indicate the shift in N_{eq}, with the upper arrow relating to the upper curve. This shift results in the curves converging at high noise contrast and there is no variation in R_{sn}. (C) The illustrated pattern of shift would result if there was no difference in N_{eq} for the two eyes (arrows are aligned). This shift results in the curves remaining separated at high noise contrasts and there is variation in R_{sn} with unmasked threshold.

were similar to functions from normal monkeys. Representative data from two amblyopic monkeys, one strabismic and one anisometropic, are shown in Fig. 2. The format of each panel is the same as that in Fig. 1A, but here the filled symbols represent amblyopic eye data and open symbols represent fellow eye data. The data for each eye are well fit by the function defined by Eq. (1). Therefore, differences in the effects of masking for the two eyes must be reflected by the relative shift of the amblyopic masking function.

Fig. 2 shows data for two monkeys at each of two spatial frequencies, one low spatial frequency for which the animal has little sensitivity difference between the eyes (top panels), and one higher spatial frequency for which a sensitivity difference is evident (bottom panels). For the low spatial frequencies, detection thresholds in noise and the fitted functions for the two eyes were very

similar, as were the derived estimates of equivalent noise (arrows). For the higher spatial frequencies, the amblyopic eye functions were shifted with respect to the fellow eye functions. However, the character of the shift was in both cases intermediate to the two extreme possibilities illustrated in Fig. 1B and C. The amblyopic eye thresholds were elevated at all noise contrast levels and the curve was shifted so that N_{eqC} was somewhat higher for the amblyopic eye than for the fellow eye. But the elevation in N_{eqC} was not as great as the elevation in unmasked threshold. This is most clearly evident from the fact that the two eyes' functions do not converge at high noise contrasts; threshold for the amblyopic eye remained more elevated than for the fellow eye. This pattern of results is representative of the pattern seen in most amblyopes, whether anisometropic or strabismic.
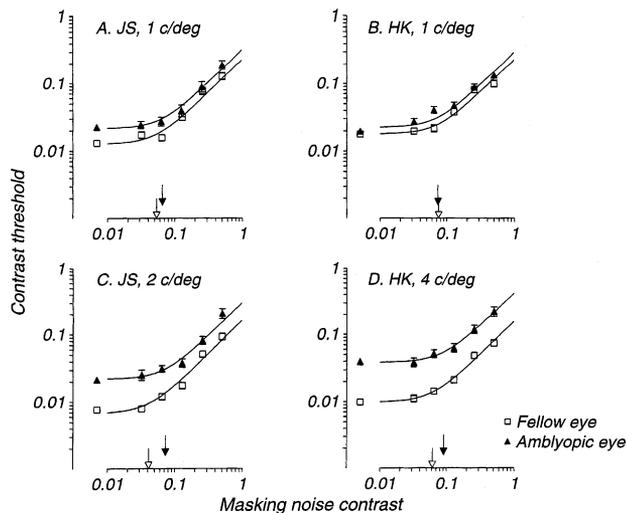
Fig. 2. Masking functions for each eye of two monkeys, one strabismic amblyope (A, C) and one anisometropic amblyope (B, D). Contrast threshold as a function of masking noise contrast is plotted for each monkey at two spatial frequencies. The format is the same as in Fig. 1A. Open symbols show fellow eye data; filled symbols show amblyopic eye data.

tor. The data for strabismic monkeys are shown in Fig. 3A and B; anisometropic monkey data are shown in Fig. 3C and D. The open and filled symbols in these panels represent data for the fellow and amblyopic eyes, respectively. The dashed lines represent a slope of 1 and are placed to pass through the geometric mean of the data. The solid lines show the slope of the best-fitting line for the full data set. For these comparisons, it is important to realize that X and Y each have associated variance. Consequently we used a fitting paradigm that used the variance in both X and Y to generate the best fit (Press, Teukolsky, Vetterling & Flannery, 1992). We did not find consistent differences between the amblyopic and fellow eyes, so the combined data are as well described by the single solid lines shown as they would be by separate lines for each data set. Although the data for the two eyes are displaced because of the difference in contrast threshold, the relationship between unmasked threshold and N_{eqC} is not different for amblyopic and fellow eyes, nor is the relationship between unmasked threshold and R_{sn}. There appears to be more scatter in signal/noise ratio for strabismics than for anisometropes, but the trends are similar in the two groups. For comparison, we plot in Fig. 3E and F, comparable data from normal monkeys (Kiorpes & Movshon, 1998). In these panels, the plus symbols are data from adults (older than 20 weeks) and the open triangles are data from infants (younger
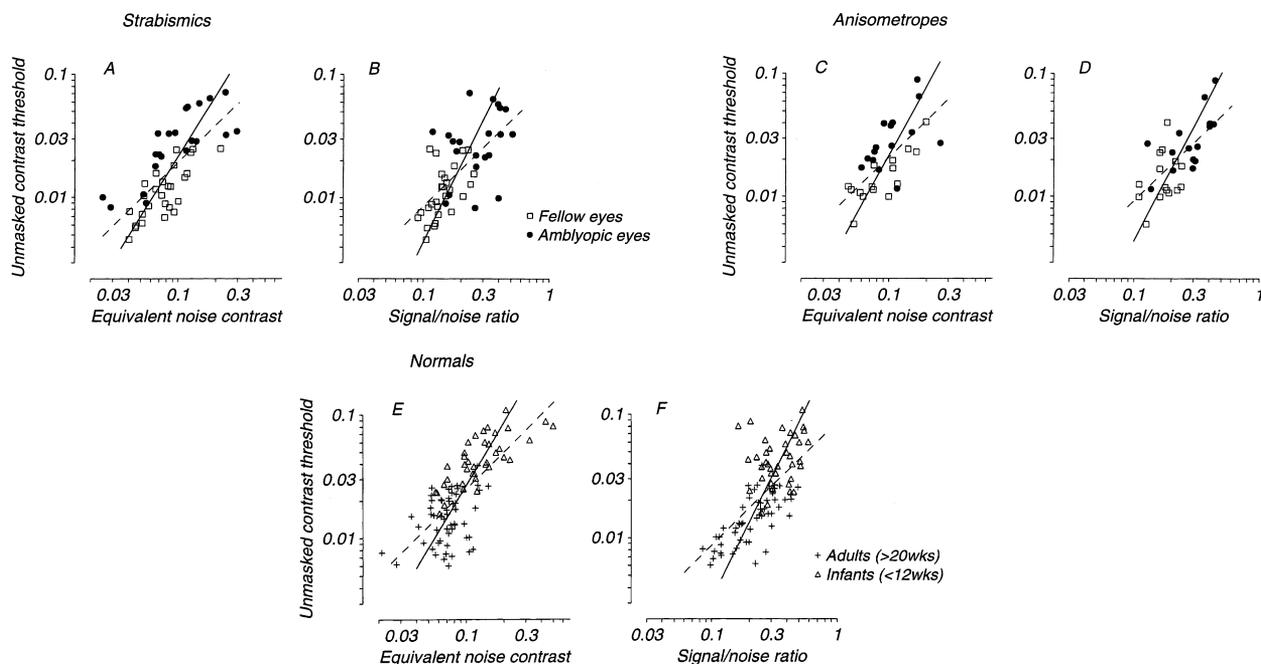
To evaluate whether the variation in unmasked threshold was more closely related to variation in equivalent intrinsic noise or signal-to-noise ratio, we plotted unmasked threshold as a function of each fac-

Fig. 3. Unmasked threshold is plotted as a function of N_{eqC} (A, C, E) and R_{sn} (B, D, F). Data for strabismic (A, B) and anisometropic (C, D) amblyopes are plotted separately; open and filled symbols represent fellow and amblyopic eyes respectively. Data for normal monkeys are plotted for comparison (E, F) (normal data from Kiorpes & Movshon, 1998). In these panels, open triangles show data from infants (age 12 weeks or younger) and pluses show data from monkeys 20 weeks of age or older. The dashed lines in all panels represent a slope of 1 and are plotted so that they traverse the geometric mean of the data set. The solid lines show the slope of the best fit to each data set (calculated taking account of the variance in both X and Y). Slope and correlation for each log-transformed data set are: (A) 1.64 ($r = 0.73$); (B) 2.09 ($r = 0.66$); (C) 1.86 ($r = 0.66$); (D) 1.95 ($r = 0.69$); (E) 1.70 ($r = 0.72$); (F) 2.05 ($r = 0.69$).
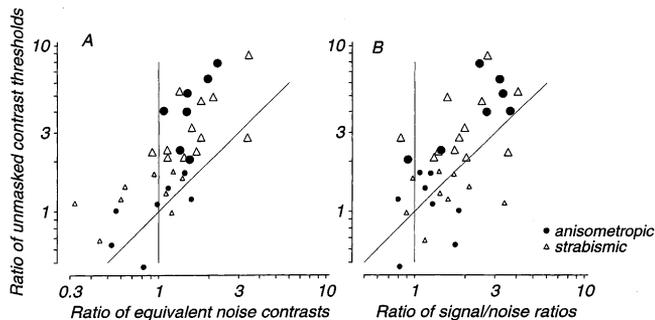
Fig. 4. Interocular ratios of unmasked threshold (amblyopic/fellow eye) are plotted as a function of the interocular ratios of N_{eqC} (A) and R_{sn} (B) for all monkeys at all spatial frequencies tested. Open symbols show data for strabismic monkeys; filled symbols show data for anisometropic monkeys; larger symbols highlight interocular threshold differences in the amblyopic range. The vertical and oblique lines represent the predictions described in Fig. 1B and C. See text for details.

than 12 weeks). The similarity between the data for amblyopes and normal monkeys is apparent. The slope of the data relating unmasked threshold to equivalent noise is consistent for amblyopic and normal monkeys, as is that relating threshold to signal/noise ratio.

It is clear from Fig. 3 that the relationships between unmasked threshold and equivalent noise, and between unmasked threshold and signal-to-noise ratio, are similar in amblyopes and normals. Both factors are correlated with threshold, but neither factor accounts completely for the variation in unmasked threshold. In amblyopes, an interocular comparison is of interest, since it relates the depth of amblyopia to changes in either N_{eqC} or R_{sn}. Fig. 4 shows the interocular comparisons. We plotted the interocular ratio of unmasked thresholds against the interocular ratios of equivalent noise contrasts (A) and signal-to-noise ratios (B). The open symbols represent data from strabismic monkeys and the filled symbols are data from anisometropic monkeys.

The solid lines, vertical and oblique, represent the patterns of shift illustrated in Fig. 1B and C. If the interocular difference was due to changes in additive noise, the ratio of unmasked thresholds would vary with the ratio of N_{eqC}; then the data in panel A would follow the oblique line and data in panel B would follow the vertical line. If the difference was due to changes in non-additive noise, the ratio of unmasked thresholds would vary with the ratio of R_{sn}; then the data in panel A would follow the vertical line and data in panel B would follow the oblique line.

Although neither outcome is perfectly supported by the data, the depth of amblyopia is more consistently related to the variation in R_{sn} than to that in N_{eqC}. If we consider the data for which the ratio of unmasked thresholds is in the amblyopic range (the difference between the eyes greater than a factor of 2; large symbols in Fig. 4), most cases show an interocular difference in threshold at high noise contrasts, that is, an elevated signal-to-noise ratio. On the contrary, while most cases show some elevation in equivalent noise in the amblyopic eye, the amount of the elevation is smaller and is not proportional to the extent of the deficit in unmasked threshold. To quantify the relationship of the data to the two predictions, we calculated the deviation of each datum (in the amblyopic range) from the vertical and oblique lines in each panel of Fig. 4: 14/19 points were closer to the vertical line in panel A, and 11/19 were closer to the oblique line in panel B. The mean-squared deviation from the two predictions for N_{eqC} was 0.066 log units from vertical and 0.148 from oblique. For R_{sn}, the mean-squared deviation was 0.137 log units from vertical and 0.089 from oblique. This outcome supports the non-additive, central limit, prediction more strongly than the additive, peripheral limit, prediction.

Finally, since amblyopia affects the high spatial frequencies to a greater degree than the low spatial frequencies, we sorted the data by spatial frequency. For the 4 c/deg stimuli, four out of five cases closely followed the central limit prediction.

4. Discussion

This study shows that the deficit in contrast threshold in amblyopic eyes is associated with an elevation in both equivalent noise contrast and signal-to-noise ratio. The deficit in unmasked contrast threshold is most closely related to the elevation in R_{sn}. Following the framework set out by Pelli (1990), these results suggest that there is some additive noise limitation on amblyopic contrast sensitivity but the non-additive component appears to be the dominant one. This pattern of results matches the expectations for a central deficit.

Our data are consistent with the results from other studies of the effects of 2-D masking noise on sensitivity in amblyopes. Nordmann et al. (1992) measured the effects of a fixed contrast power masking noise on contrast sensitivity for grating stimuli. The amblyopes were strabismic, anisometropic or both, although most had comparatively mild deficits in unmasked contrast sensitivity. The contrast of the 2-D noise was fixed at a level that elevated threshold 20–40% depending on the spatial frequency of the grating. They found no difference in the effect of noise on amblyopic and fellow eyes: the ratio of contrast threshold in noise to the no-noise threshold was comparable for the two eyes of these amblyopes and was similar to that for normal controls. This result implies a vertical shift of the masking function, rather than an effect due to elevated equivalent noise. Levi et al. (in preparation) conducted a comparable experiment using letter identification

rather than grating detection. They estimated equivalent noise and 'efficiency' (relative performance at high noise contrast) in various amblyopic observers. Most observers had similar equivalent noise contrast for amblyopic and fellow eyes but showed reduced efficiency with high noise contrast at high letter spatial frequencies. As the frequency content of the letter approached the acuity limit, the ability of the observers to identify the letters in noise dropped dramatically. This result is consistent with our findings of a comparatively greater effect in amblyopic signal-to-noise ratio than in equivalent noise at the higher spatial frequencies.

Our previous study of the limitations on the development of contrast threshold in infant monkeys suggested that normal development is associated with relatively greater variation in equivalent noise than in signal-to-noise (Kiorpes & Movshon, 1998). This association is evident from the normal data shown in Fig. 3E and F: notice that for the infants as a group (open triangles), there is little overall variation in R_{sn} whereas there is substantial variation in N_{eqC}. This trend was evident at all spatial frequencies except the highest, 4.2 c/deg, where there was a relatively stronger relationship between contrast threshold and R_{sn}. By analogy with the infants, we expected a larger effect on signal-to-noise ratio at high spatial frequencies in the amblyopes. This was indeed what we found. However this pattern was predominant for lower spatial frequencies as well in cases where there was a substantial deficit in unmasked contrast threshold. The comparison of the infant pattern to that of the amblyopes suggests that the mechanism(s) associated with equivalent noise are less affected by early visual experience than those associated with signal detection in high levels of noise.

In the present study, we found that amblyopia is more strongly associated with an elevation in signal-to-noise ratio than equivalent noise. This pattern of results, in the Pelli (1990) framework, suggests that the site of the amblyopic deficit is predominantly central whereas the infant pattern is predominantly peripheral. Pelli partitioned the limitations on contrast detection into two factors, which he derived from an ideal observer analysis of visual system function. He described an additive factor, thought to be associated with the input stages of the visual system, and a multiplicative factor, thought to be associated with more central processes in visual system. Pelli argued that the noise that is captured by N_{eqC} is early in the visual system by analogy with engineering principles (Pelli, 1990), and by the demonstration that this noise must arise earlier in the visual system than any significant non-linearity (Pelli, 1991).

The question that immediately comes to mind then is, what is meant by a central or peripheral deficit in the context of our amblyopes? The typical presumption is that a central deficit is a one of cortical origin. There is good evidence for this in the case of amblyopic and visually deprived monkeys. Electrophysiological studies show deficits in contrast sensitivity, acuity, and binocular interaction in single cells in striate cortex of monkeys with behaviorally verified amblyopia (Movshon, Eggers, Gizzi, Hendrickson, Kiorpes & Boothe, 1987; Crawford, Harwerth, Chino & Smith, 1996; Smith, Chino, Ni, Cheng, Crawford & Harwerth, 1997; Kiorpes et al., 1998). These deficits are not evident at earlier levels of the visual pathways. Comparable studies of cells in the LGN in amblyopic and visually deprived monkeys have shown surprisingly normal spatial and temporal responsiveness (Movshon et al., 1987; Blakemore & Vital-Durand, 1986; Levitt, Movshon, Sherman & Spear, 1989). It is therefore reasonable to suggest that the site of increased signal-to-noise in amblyopes is at the level of striate cortex or beyond. This conclusion is consistent with Pelli's analysis (described above) since significant non-linearities may not arise prior to striate cortex in cats and monkeys (e.g. Movshon, Thompson & Tolhurst, 1978a,b; DeValois, Albrecht & Thorell, 1982; Carandini, Heeger & Movshon, 1997).

However, the interpretation becomes more complicated in light of our recent electrophysiological studies of the infant visual system (Movshon, Kiorpes, Hawken, Skoczenski, Cavanaugh & Graham, 1997a,b). We studied contrast sensitivity and spatial resolution of single neurons at the level of the LGN in young monkeys, in both the absence and the presence of the same spatiotemporal broadband noise used in this study and in our psychophysical study of infant development. The data suggest that the development of LGN cell properties is not sufficient to account for the behaviorally measured development of contrast sensitivity, nor is the response of infant neurons to the presence of masking noise substantially different from that in adult LGN. Therefore, the 'peripheral' limit on infant contrast sensitivity is likely to be *central* to the LGN. It is possible then that equivalent noise and signal-to-noise ratio reflect different properties of the same neurons or, at the very least, reflect properties of different cortical cells at some level. Further physiological analysis will be needed to gain a clear interpretation of these results.

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