



Spatial-frequency properties of letter identification in amblyopia

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Abstract

Amblyopia is characterized by a deficit in identifying small letters (acuity deficit) in the absence of identifiable ocular pathology. One explanation for this deficit is that the amblyopic visual system lacks appropriate channels tuned to high spatial frequencies for identifying small letters. The purpose of this study was to examine the spatial-frequency properties of letter identification in the amblyopic visual system. To do so, we measured contrast thresholds for identifying letters that were band-pass filtered to different bands of spatial frequencies, for letter sizes ranging from 2× to 19.2× larger than acuity letters. Letters were digitally filtered using a set of band-pass filters, with peak object spatial frequencies ranging from 0.88 to 10 c/letter. The bandwidth of the filters was 1 octave. For any given letter size, contrast sensitivity for identifying letters exhibits a spatial-tuning function. The shape of these tuning functions was found to be similar between amblyopic and non-amblyopic eyes, and across all letter sizes. The peak of these functions shifted progressively toward lower object spatial frequency when the letter size became smaller. When compared with the non-amblyopic eyes, the amblyopic eyes have a limited range of tuning functions sensitive to letters. However, when scaled with respect to acuity, the relationship between the peak frequency of the tuning functions and letter size becomes essentially identical in the amblyopic and non-amblyopic eyes. An ideal-observer analysis that takes into account spectral information about letter identity and the contrast-sensitivity function of the observer, but does not invoke narrow-band channels, also shows that the properties of the tuning functions for letter identification are similar between the amblyopic and non-amblyopic eyes. We conclude that the deficit in identifying small letters in amblyopes is not attributable to differences in the shape or selection of “channels”, when compared with the normal visual system. Rather, it is a consequence of the difference in the resolution limit between the amblyopic and the non-amblyopic eyes. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Letter identification; Amblyopia; Spatial-frequency channel; Contrast sensitivity

1. Introduction

Amblyopia is a developmental disorder of spatial vision, which is usually identified by impaired vision in one eye that is not attributable to an identifiable ocular pathology. It is almost always accompanied by strabismus and/or anisometropia.

Traditionally, amblyopia is defined by a loss of visual acuity (for a list of definitions of amblyopia, refer to Ciuffreda, Levi, & Selenow, 1991, pp. 10–14), which, in clinical settings, usually means a reduction in high-contrast letter acuity. Amblyopes also demonstrate substantial loss in contrast sensitivity for detecting, as well as identifying small letters (Lawwill & Burian,

1966). To date, the cause and nature of the acuity deficit exhibited by the amblyopes is still largely unresolved. One simple explanation is that the amblyopic visual system does not have the appropriate high spatial-frequency channels to detect or identify small letters. Because amblyopic contrast sensitivity functions (CSFs) (as assessed using sine-wave gratings) usually exhibit a deficit in the mid spatial frequencies in addition to the high frequency loss (e.g. Bradley & Freeman, 1981; Hess & Howell, 1977; Levi & Harwerth, 1977), amblyopes might in fact have a loss in sensitivity for a range of small to medium letter sizes. If so, the channels used by amblyopes for identifying letters may be sub-optimal for a range of letter sizes. Recently, Hess, Dakin, Tewfik, and Brown (2001) suggested that channel selection is normal in amblyopia for discriminating the orientation of a Landolt C. Their findings, however, may not

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pertain to the identification of letters. Deriving the identity of a letter among the entire alphabet set involves more than examining the differences in the amplitude spectrum between horizontal and vertical orientations, as is the case for discriminating the orientation of a Landolt C (Bondarko & Danilova, 1997; Hess, Dakin, & Kapoor, 2000). The purpose of this study, therefore, was to examine the spatial-frequency properties of letter identification in the amblyopic visual system, and compare them to those in the normal visual system. Based on the empirical evidence suggesting a close resemblance in visual functions between strabismic amblyopes and normal peripheral vision (e.g., Chung & Levi, 1997; Levi & Klein, 1985; Levi, Klein, & Yap, 1987; Levi, Klein, & Sharma, 1999; Levi, Klein, Sharma, & Nguyen, 2000), we were especially interested in comparing the properties of letter identification in amblyopes to those in the normal periphery.

In normal vision, the properties of letter identification are quite well understood based on a channel model. Parish and Sperling (1991), and Solomon and Pelli (1994) proposed that letter identification in the normal fovea is mediated by a single spatial-frequency channel with a constant object-frequency in *c*/letter, independent of letter size. However, subsequent studies (Alexander, Xie, & Derlacki, 1994; Chung, Legge, & Tjan, in press; Majaj, Pelli, Kurshan, & Palomares, in press) have shown that channel frequency shifts toward lower object spatial frequency as letter size becomes smaller. In normal periphery, channel frequency also shifts to a lower object spatial frequency when letters become smaller (Chung et al., in press; Majaj et al., in press). In this study, we will use the range of the channel frequency, and how it changes with letter size, to form the key comparisons of the spatial-frequency properties of letter identification between amblyopic and normal vision.

Recently, an alternative to the channel model for letter identification has been proposed by Chung et al. (in press). According to Chung et al., the spatial-frequency tuning properties for letter identification can be accounted for by an observer's contrast sensitivity function (CSF) and the letter-identity information as derived from an ideal observer for a letter-identification task. This result obviates the need to invoke specific channels for letter identification. Here, we will analyze our amblyopic data using this alternative CSF-ideal-observer model to see whether the amblyopic data, like those of normal observers, can be accounted for without invoking "letter channels".

To evaluate the properties of letter identification in amblyopes, we first measured contrast thresholds for identifying band-pass filtered letters as a function of letter object frequency, and for a range of letter sizes. These measurements yield a tuning function of contrast sensitivity vs. letter object frequency for letters of a

given size, analogous to a CSF measured using sinewave gratings. Then, we compared the following four key properties of letter identification in amblyopes, with those in non-amblyopic vision: (1) the relationship between the peak tuning frequency and nominal letter frequency (which is proportional to the reciprocal of letter size); (2) the range of peak tuning frequencies used for identifying letters of different sizes; (3) whether the peak tuning frequency is lower in amblyopic than non-amblyopic eyes for letters of a given size; and (4) the bandwidth of the tuning functions. In addition, we also made comparisons of these key properties with corresponding findings for normal peripheral vision (Chung et al., submitted). If amblyopic vision is similar to normal peripheral vision, then we expect the following findings: peak tuning frequency relates to nominal letter frequency by a power function with an exponent of approximately 0.7; the range of peak tuning frequencies is shifted toward lower nominal letter frequencies (i.e., larger letter sizes); peak tuning frequency in the amblyopic eyes is lower than that in the non-amblyopic eyes for letters of a given size; and comparable bandwidth values to those found in normal peripheral vision. To anticipate, our results show that the spatial-frequency properties for letter identification in the amblyopic visual system are similar to those in the non-amblyopic visual system in many ways, and closely resemble those in normal peripheral vision.

2. Methods

Contrast thresholds for identifying single, band-pass filtered letters were measured for a range of letter object frequencies (specified as the center-frequency of the band-pass filters used to generate the letter stimuli), and as a function of letter sizes in five observers with strabismic amblyopia and one observer with anisometropic amblyopia but no strabismus. Table 1 summarizes the visual characteristics of these amblyopic observers. Because it is still controversial as to whether the non-amblyopic eye of an amblyopic observer is truly normal, we included two observers with normal vision as control. Specific details of the band-pass filters and the process of generating the letter stimuli were described elsewhere (Chung, Levi, & Legge, 2001). In brief, we digitally filtered each of the 26 lower-case Times-Roman letters using a set of eight raised cosine log filters. We used all 26 lower-case letters instead of a limited set of letters because our interest was to understand the properties of letter identification in general, and not the properties that are associated with only a finite set of letters. Inevitably, the use of 26 instead of a finite set of letters could potentially introduce more measurement noise in our data. Each of the band-pass filters has a 1-octave bandwidth (full-width at half-height) and is ra-

Table 1
Visual characteristics of the amblyopic observers

Observer	Age	Sex	Eye	Rx	Acuity	Unfiltered letter acuity	Fixation	Strabismus
AJ	27	F	OD	+5.50/ - 2.50 × 20	20/60	0.38°	1.5° temporal Central	Constant RXT 4Δ
			OS	-0.25	20/15	0.19°		
CB	37	M	OD	+4.25	20/15	0.30°	Central 0.75–1° nasal	Constant LET 4Δ
			OS	-9.75/ - 0.75 × 140	20/200	0.75°		
JB	40	M	OD	+1.75/ - 0.50 × 142	20/38	0.32°	Central 0.5° nasal	Constant RXT 6Δ
			OS	+1.25/ - 1.00 × 25	20/20	0.16°		
QM	18	M	OD	-0.25	20/20-	0.16°	Central 3° nasal and superior	Constant LET 7Δ L Hyper 1Δ
			OS	+2.25/ - 2.75 × 180	20/60	0.38°		
RH	32	M	OD	-1.00/ - 0.50 × 170	20/15	0.13°	Central Unsteady	Microtropia LET 2Δ
			OS	-1.50/ - 1.50 × 10	20/36	0.30°		
RJ	53	M	OD	+0.50/ - 0.25 × 95	20/14	0.15°	Central Central	None
			OS	+2.50/ - 0.75 × 125	20/57	0.31°		

dially symmetrical in the log-frequency domain (Alexander et al., 1994; Peli, 1990). The bandwidth of the filters has a direct impact on the bandwidth of the spatial-tuning functions that we obtained, such that a filter of a broader bandwidth would yield broader spatial-tuning functions. The center-frequency of the filters ranges from 0.88 to 10 c/letter, in half-octave steps. The filter can be described by the following equation:

Amplitude at radial frequency fr

$$= \frac{1.0 + \cos\left(\pi \frac{\log(fr) - \log(ctr)}{\log(cut) - \log(ctr)}\right)}{2}$$

where ctr represents the spatial frequency corresponding to the peak amplitude of the filter (center frequency) and cut represents the frequency at which the amplitude of the filter drops to zero (cut-off frequency). Fig. 1 shows a

set of these filtered images of the letter “s”. Because our goal was to identify the crucial band of spatial frequencies for letter identification, we adopted a nominal contrast definition. We operationally assigned a contrast of 100% to all filtered images, after they were derived from a 100% contrast unfiltered letter through filtering, and without rescaling. In other words, even though a letter filtered with a high spatial-frequency band-pass filter contains less energy than one filtered with a low spatial-frequency filter, these two letters are still considered to have the same 100% nominal letter contrast. For example, if letters filtered with the 2.5 c/letter band-pass filter need to be attenuated by a factor of 20 to reach threshold, then the nominal threshold contrast would be 0.05 of that of their unfiltered parent letters, or, 5%. In essence, we were measuring the contrast required for a certain band of spatial frequencies within an

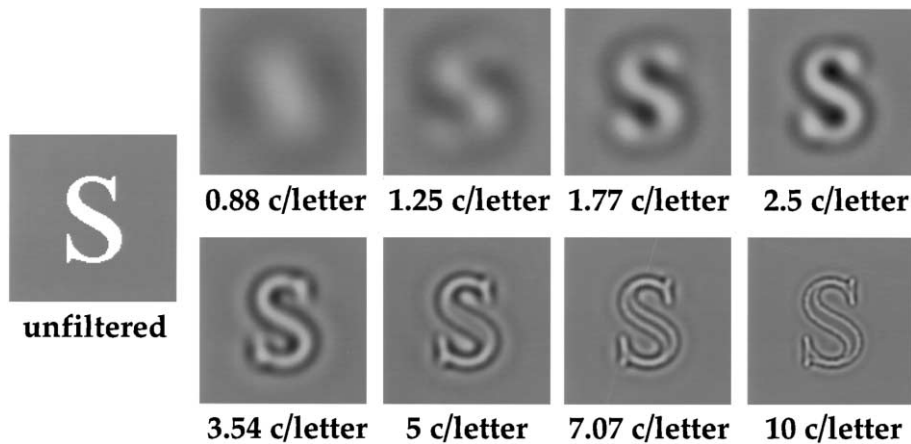


Fig. 1. Samples of the filtered letters. The spatial frequency given underneath each letter sample represents the peak object frequency of the band-pass filter.

unfiltered letter to reach threshold. This contrast definition facilitates comparison of data across observers and testing conditions.

During each trial, one of the 26 letters was randomly selected and presented in the middle of an Apple high-resolution monochrome monitor, equipped with an ISR video attenuator, for a duration of 150 ms. The mean luminance of the monitor was about 45 cd/m². The task of the observer was to identify the letter being presented by indicating his/her response using a computer mouse. An audio tone denoted each correct response. The host computer was either a PowerMac 6100 or a G3 PowerMac. We used custom-written software to run the experiment. Presentation and contrast-control of the stimuli were achieved using the VideoToolbox software (Pelli & Zhang, 1991). We used a 3 down-1 up staircase psychophysical procedure to track the contrast threshold corresponding to a 79% observed correct probability on the psychometric function. Six reversals were used in each staircase and the average of the last four reversals was taken as the threshold for that block of trials. Each datum reported in the study represents the average of 4–6 independent measures of threshold for the same condition.

To examine the effect of letter size, we first used unfiltered letters to determine the smallest letter that could be reliably identified. This “letter acuity” was tracked using the same staircase procedure, and was determined separately for the amblyopic and non-amblyopic eyes of the amblyopic observers, and for one eye of the normal observers. We then tested letter sizes 2× to 19.2× larger than the letter acuity. Table 1 lists these unfiltered letter acuities for the amblyopic observers. The sequence of testing the various conditions (eyes × letter size × letter object frequency) was randomized within and between observers.

As mentioned in Section 1, we also applied the CSF-ideal-observer analysis to the data of our amblyopic observers. To do so, we first obtained CSF measurements from two of the amblyopic observers, AJ and RH. We then combined these CSFs with the letter-identity information derived from an ideal-observer to obtain the predicted peak tuning frequencies for a range of letter sizes. Details of how the letter-identity information was derived and how the predicted peak tuning frequencies were calculated can be found in Chung et al. (in press). The CSFs of the amblyopic observers were measured using a Gabor detection task, at a mean luminance of 50 cd/m², closely matched to the mean luminance of the present study.

3. Results

Relative contrast sensitivity, the contrast sensitivity for identifying filtered letters normalized to the contrast

sensitivity for identifying unfiltered letters, is plotted as a function of the center-frequency of band-pass filters for the six amblyopic observers in Fig. 2. When plotted as relative contrast sensitivity, a band with a relative contrast sensitivity of 0.5 means that the nominal threshold contrast of this band was twice as high as that of an unfiltered letter. In other words, the unfiltered letter could be attenuated by an extra factor of two in contrast (compared with letters filtered with this band of frequencies), before reaching its threshold.

Each data set represents the measurements obtained at one letter size. All data sets demonstrate spatial-tuning characteristics. To describe these spatial-tuning functions quantitatively, we fitted each data set, on log-log axes, with a parabolic function¹ of the form:

$\log(\text{relative contrast sensitivity})$

$$= \log(\text{amplitude}) - \frac{4}{\log(2)\sigma^2} (\log(\text{sf}) - \log(\text{sf}_p))^2$$

where amplitude represents the full-height of the function, sf is spatial frequency, sf_p is the peak tuning frequency and σ is the bandwidth of the function in octaves.

It is interesting to note that the peak relative contrast sensitivity of all tuning functions is less than a value of 1.0, suggesting that the threshold for identifying any letter with a limited band of spatial frequencies is always higher than that for identifying the unfiltered parent letters. This is clear evidence that the visual system pools information from different bands of spatial frequencies when identifying broadband or unfiltered letters.

While there are individual differences among the observers, the general trend of their data seems to be very similar. Also, there is no clear indication that the only amblyope who did not have strabismus (observer RJ) behaved any differently from the five amblyopes with strabismus. Therefore, for the rest of the paper, analyses will be based on group data, but individual data are given as well and are represented by different symbols in the figures.

For both amblyopic and non-amblyopic eyes, the peak of the spatial-tuning function for letter identification shifts toward lower spatial frequencies when letter size approaches the acuity-limit, consistent with an earlier report (Alexander et al., 1994). This shift is an indication that the identification of letters of various sizes is not mediated by channels that peak at the same

¹ In addition to a parabolic function, we have fitted our data using single Gaussian and split Gaussian functions. The main results remain unchanged. The use of a parabolic function facilitates the calculation of the bandwidth, which is defined as full-width at half-height (when the peak amplitude drops by 0.3 log units). Because the height of a Gaussian function is co-determined by two parameters, in some cases, the bandwidths could not be determined (when the amplitude of the Gaussian function was small).

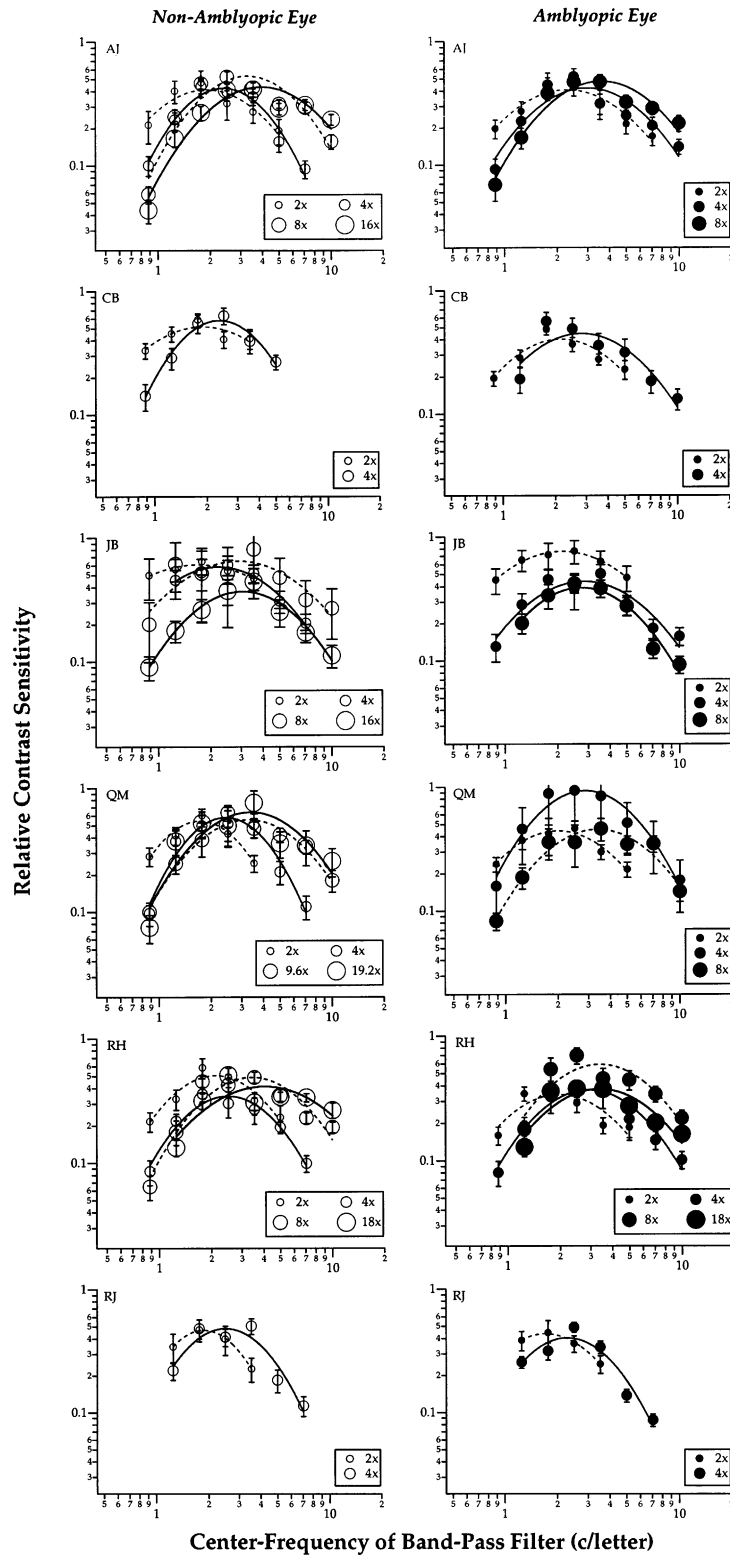


Fig. 2. Relative contrast sensitivity is plotted as a function of letter object frequency, represented by the center-frequency of the band-pass filter ($c/$ letter), for the six amblyopic observers. Data from the two eyes of each observers are presented separately (non-amblyopic eye on the left and amblyopic eye on the right). Each panel includes data obtained at different letter sizes, denoted by the size of the symbols. The fitted curve is a parabolic function (see text for details). Error bars represent ± 1 s.e.m.

object spatial frequency, in agreement with the finding in the normal fovea and periphery (Chung et al., in press;

Majaj et al., in press). Fig. 3 plots the peak tuning frequency (parameter sf_p from the curve-fits) as a function

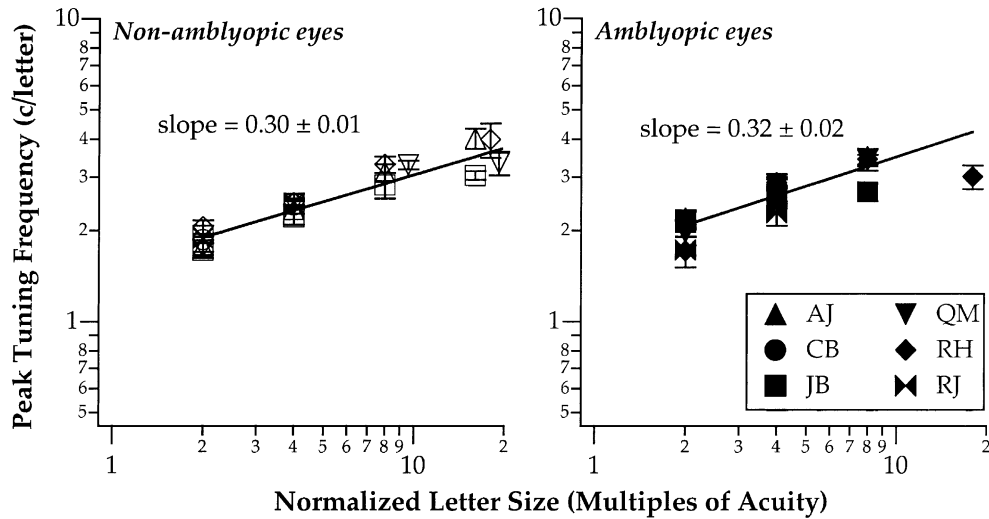


Fig. 3. Peak tuning frequency (c/letter) is plotted as a function of letter size normalized to the acuity, for the non-amblyopic eyes (left) and amblyopic eyes (right). Different symbols represent data from different observers. The peak tuning frequency of the spatial-tuning function used for identifying a letter changes with the size of the letter, for both non-amblyopic and amblyopic eyes alike. Error bars represent ± 1 s.e.m, derived from curve-fitting as shown in Fig. 2.

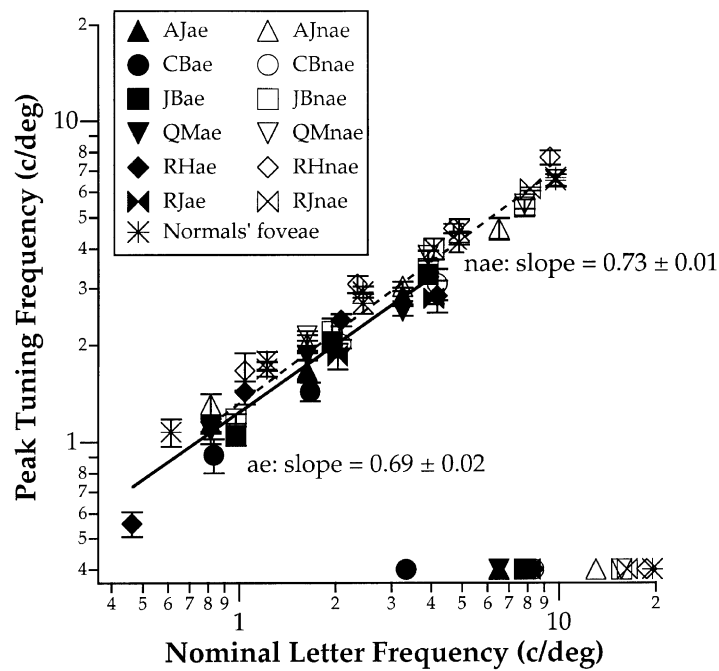


Fig. 4. Peak tuning frequency (c/deg) is plotted as a function of nominal letter frequency (c/deg), for the amblyopic eyes (ae, filled symbols), non-amblyopic eyes (nae, unfilled symbols) and the normal observers (asterisks). Different symbols represent data from different amblyopic observers. The solid line is the power function fitted to the amblyopic data set; whereas the dashed line is the power function fitted to the non-amblyopic data set (data from the normal observers were not included in the curve-fitting). The row of datum points lying just above the abscissa represents the acuities of the observers (converted to c/deg). Error bars represent ± 1 s.e.m, derived from curve-fitting as shown in Fig. 2.

of letter size. To facilitate comparison between the amblyopic and non-amblyopic eyes, letter sizes are plotted as multiples of the acuity, rather than the physical letter size in degrees. Clearly, the peak tuning frequency does not remain constant for the range of letter sizes tested.

The first three key properties of letter identification relate to how the peak tuning frequency changes with letter size. In Fig. 4 we plotted peak tuning frequency, converted into retinal-based spatial frequencies in c/deg after taking into account the letter size, as a function of

nominal letter frequency. From this figure, peak tuning frequency increases continuously with nominal letter frequency, over the entire range of letter sizes tested in the study ($\approx 2\text{--}20$ times the acuity-limit illustrated for each observer by the symbols near the abscissa). Over this range of letter sizes, the relationship between peak tuning frequency and nominal letter frequency was similar in amblyopic and non-amblyopic eyes, but there are no tuning functions tuned to high nominal letter frequencies (small letter sizes) in the amblyopic visual system. To assess the relationship between peak tuning frequency and nominal letter frequencies, we fitted a power function (straight line on log–log axes) separately to the data set of the amblyopic and the non-amblyopic eyes. The log–log slope of these functions are very similar—0.69 and 0.73 for the amblyopic and non-amblyopic eyes, respectively.

Although the log–log slopes are very similar between the amblyopic and non-amblyopic data sets, there appears to be a small, but consistent vertical offset between the two data sets. The presence of this vertical offset, representing a shift in the peak tuning frequency, suggests that for identifying a letter of the same physical size, the peak tuning frequency in some amblyopic eyes is slightly lower than that in their non-amblyopic counterparts. To determine the magnitude of this shift in peak tuning frequency, we refitted the amblyopic and non-amblyopic data sets with a power function of a fixed log–log slope of 0.71, the average between the log–log slopes reported in Fig. 4, and determined the y -intercepts (the values of y at $x = 1$ in our log–log plots)

for the two data sets. From the curve-fitting, the y -intercept was found to be 1.22 ± 0.01 and 1.36 ± 0.01 for the amblyopic and non-amblyopic eyes, respectively, representing a peak tuning frequency of, on average, 10% lower in the amblyopic eyes, compared with the non-amblyopic eyes. This shift is smaller than the one between the fovea and the periphery (25% shift at 5° , and 33% shift at 10° eccentricity (see Chung et al., in press)).

The presence of a mere 10% shift between the data sets of the amblyopic and non-amblyopic eyes rejects the notion that the deficit in identifying small letters in amblyopia is due to the reliance on an abnormally low spatial-frequency channel, which would have otherwise predicted a much larger vertical offset between the amblyopic and non-amblyopic data sets.

The lack of tuning functions tuned to high nominal letter frequencies in the amblyopic eyes is not surprising, since this is the fundamental definition for amblyopia. However, by normalizing both the peak tuning frequencies and the nominal letter frequencies to the individual observer’s acuity (expressed in c/deg), the data of the amblyopic eyes can be brought into close agreement with those for the normal and non-amblyopic eyes (Fig. 5). This normalization corresponds to a shift of the amblyopic eye data diagonally in the plot, and, as can be seen in Fig. 5, it compensates quite well for the limited range of tuning functions in the amblyopic eyes. This finding suggests that as long as a letter can be resolved, the channel for identifying the letter is more or less normal in the amblyopic eyes.

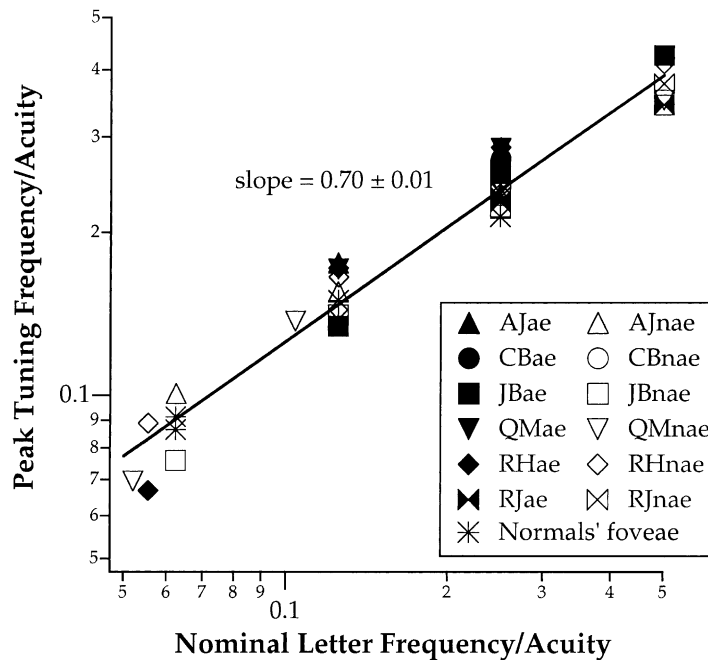


Fig. 5. Peak tuning frequency and nominal letter frequency as shown in Fig. 4 are normalized to the acuity of each individual observer. As a result, data from the two eyes of the amblyopic observers and those from the normal observers all collapse into one single set of data.

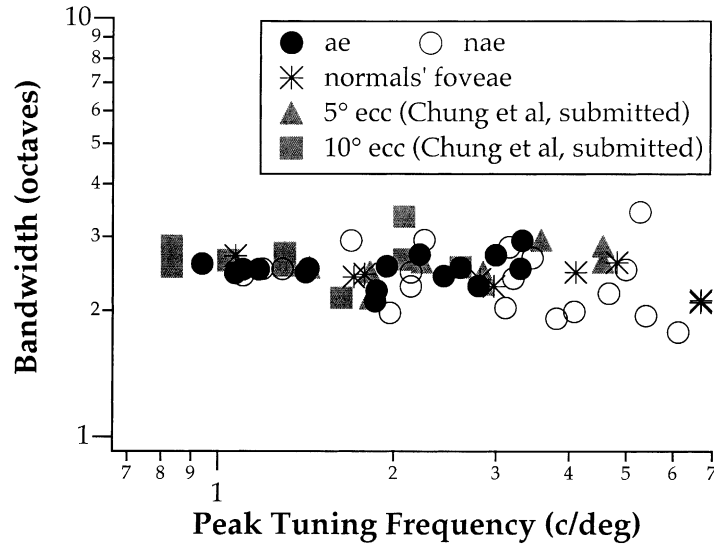


Fig. 6. Bandwidth (octaves) is plotted as a function of the peak tuning frequency, for the amblyopic eyes, non-amblyopic eyes and the fovea of the normal observers. Bandwidth measurements obtained at 5° and 10° eccentricity in normal periphery are also replotted here from Chung et al. (in press). In general, the bandwidths are very similar across the tuning functions and do not differ among the amblyopic eyes, non-amblyopic eyes, normal fovea and periphery.

The fourth key property of letter identification that we were interested in is the bandwidth, or the frequency-selectivity of the spatial-tuning functions. In Fig. 6, we compared the bandwidths of the tuning functions, defined as the full-width at half-height, for the amblyopic vs. non-amblyopic eyes. As shown in Fig. 6, the bandwidths are relatively constant across the range of peak tuning frequencies, and are very similar between the amblyopic (averages 2.51 ± 0.19 octaves) and the non-amblyopic eyes (averages 2.40 ± 0.42 octaves). With respect to letter size, the bandwidths are very similar across the various letter sizes. These bandwidths are also comparable with those obtained at 5° and 10° in

normal periphery (data replotted from Chung et al., in press).

As control measurements, we also tested two observers with normal vision. Their spatial-tuning functions for identifying letters are shown in Fig. 7. The change in the shape of the spatial-tuning function with letter size closely resembles that shown by the amblyopic observers. We included in Fig. 4 peak tuning frequencies as a function of nominal letter frequencies obtained from the normal observers (denoted by asterisk symbols). Clearly, the normal observers' data fall within the same general zone as the data set obtained from the non-amblyopic eyes of the amblyopic observers. When we

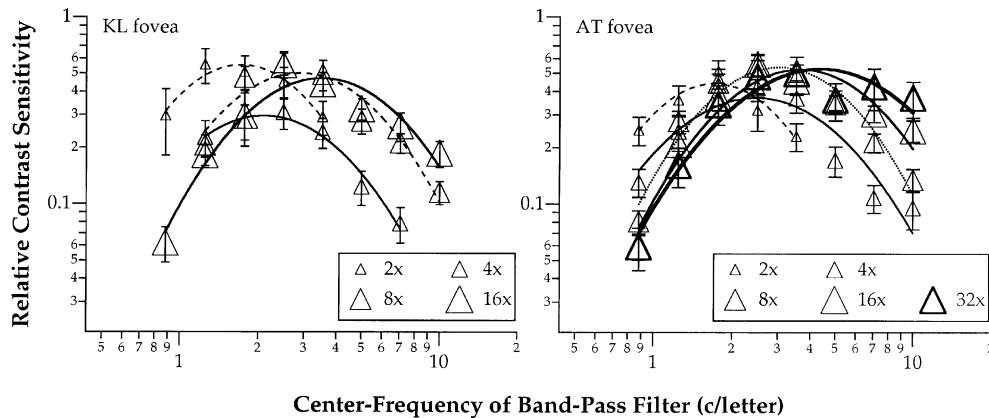


Fig. 7. Relative contrast sensitivity is plotted as a function of letter object frequency, represented by the center-frequency of the band-pass filter (c/letter), for the two normal observers. Each panel includes data obtained at different letter sizes, denoted by the size of the symbols. The fitted curve is a parabolic function (see text for details). Error bars represent ± 1 s.e.m.

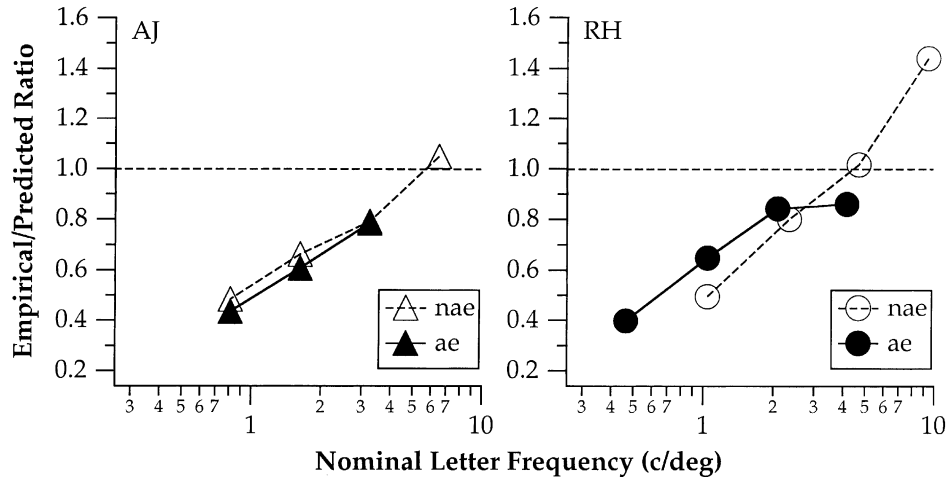


Fig. 8. Ratio between the empirically determined, and the predicted peak tuning frequency, is plotted as a function of nominal letter frequency (c/deg), for both the amblyopic and the non-amblyopic eyes of observers AJ and RH. A value of one (represented by the dashed lines) indicates that the empirical and the predicted values are the same.

normalized the normal observers' data with respect to the acuity-limit, as expected, the normalized data from the normal observers and those from the two eyes of the amblyopic observers all follow the same trend (Fig. 5).

With respect to frequency selectivity, Fig. 6 shows that the bandwidths derived from the normal observers' data are very similar in magnitude to those of the amblyopic observers, suggesting that the spatial-tuning functions for identifying letters in normal observers share similar frequency selectivity with those in amblyopic observers.

Can the amblyopes' spatial-tuning properties for letter identification be accounted for by their CSF and the letter-identity information, as is the case for normal observers? Results from the CSF-ideal-observer analysis are presented in Fig. 8, where the ratios between empirical and predicted peak tuning frequencies are plotted for a range of nominal letter frequencies, for observers AJ and RH. Contrary to our expectation (based on the findings of Chung et al. (in press)), there is a discrepancy between the empirical and predicted value for most letter sizes. For larger letters, the predicted value overestimates the peak tuning frequency (i.e., ratio < 1), and the overestimation increases with letter size (i.e., it is largest at low nominal letter frequencies). There is some indication that for very small letters, the predicted value under-estimates the peak tuning frequency (i.e., ratio > 1). This discrepancy will be addressed in the Discussion section. The important point however, is that the *ratio* at all letter frequencies is remarkably similar between the amblyopic and the non-amblyopic eyes. This suggests that as long as we take into account the letter-identity information (obtained from the ideal-observer) and the differences in spatial resolution between the amblyopic and non-amblyopic eyes (the

CSFs), the properties of letter identification are similar in the amblyopic and non-amblyopic eyes.

4. Discussion

The primary purpose of this study was to examine the spatial-frequency properties of letter identification in the amblyopic visual system, and compare them to those in the normal visual system. To facilitate the comparison, we focused on four key properties of letter identification: (1) the exponent (i.e., the log-log slope) of the power function relating peak tuning frequency and nominal letter frequency; (2) the range of peak tuning frequencies for identifying letters; (3) the presence or absence of a shift in peak tuning frequency between amblyopic and non-amblyopic eyes and (4) the bandwidth of the tuning functions.

In relation to peak tuning frequency and nominal letter frequency, we have three principal findings. First, we found that peak tuning frequency grows as a power function of nominal letter frequency with an exponent of about 0.7, in both amblyopic and non-amblyopic eyes alike. This exponent agrees well with that reported in earlier studies (Chung et al., in press; Majaj et al., in press). Second, amblyopic eyes lack tuning functions tuned to high frequency (i.e., small letters), which is consistent with the acuity deficit defining amblyopia. Third, there is a small, but consistent, shift in peak frequencies for identifying letters between the amblyopic and non-amblyopic eyes. These findings, together with the similar bandwidth of the tuning functions between the amblyopic and the non-amblyopic eyes, are strong evidence in support of the proposition that the amblyopic visual system is highly similar to normal or

non-amblyopic vision with respect to the spatial-frequency properties of letter identification.

The finding that the frequency range of tuning functions for letter identification is shifted toward lower spatial frequencies in the amblyopic eyes is consistent with the finding of Levi et al. (unpublished data), who used critical-band noise masking to derive the sensitive channels for letter identification. One difficulty with critical-band noise masking is that the contrast thresholds for identifying letters are already highly elevated in the amblyopic eyes, which makes it difficult to achieve enough noise on computer displays to effectively raise thresholds for small letters. Thus, the filtered letter technique used here may provide more robust estimates of the spatial-frequency properties of letter identification in the amblyopic visual system, near the acuity limit.

Given our findings, one logical question that arises is—are the channels in the amblyopic visual system “normal”? Using adaptation (Hess, 1980) and masking (Levi & Harwerth, 1982) paradigms and sine-wave gratings as stimuli, the bandwidths and the amplitudes of the adaptation and masking threshold-elevation functions are found to be very similar between the amblyopic and non-amblyopic eyes. In the present study, using filtered letters to limit the band of spatial frequencies in the stimuli, we also found that the bandwidths of the spatial-tuning functions for letter identification are essentially identical between the amblyopic (2.51 ± 0.19 octaves) and non-amblyopic eyes (2.40 ± 0.42 octaves). These values are similar to the tuning bandwidth for grating detection (Hess, 1980; Kiper, Gegenfurtner, & Kiorpes, 1995; Levi & Harwerth, 1982), line detection and Vernier discrimination (Levi, Waugh, & Beard, 1994). When we normalized the peak tuning frequency and nominal letter frequency to the individual observer’s acuity, for the two eyes separately, data for the amblyopic and non-amblyopic eyes all collapse into one single function (Fig. 5). Our results are also consistent with a recent study showing that amblyopic eyes do select an optimum channel for identifying the orientation of a single letter C that is close to the acuity-limit (Hess et al., 2001). All these pieces of evidence converge to suggest that the channels in the amblyopic eyes are just like those found in the normal visual system.

Using an ideal-observer analysis, Chung et al. (in press) showed that the spatial-frequency properties of letter identification in normal fovea and periphery are determined by two factors: the letter-identity information as a function of object spatial frequency, and the human CSF. They showed that when a human CSF is incorporated into an ideal-observer model, the relationship between peak tuning frequency and letter size, and the bandwidth of the tuning functions, resemble closely those of human observers, in both the fovea and 10° eccentricity. In other words, human performance in

identifying filtered letters can be accounted for solely by the CSF and the letter-identity information, without invoking narrow-band spatial-frequency channels. Here, using the same analysis to predict peak tuning frequencies for our amblyopic observers, we found that for most letter sizes, the predicted values do not match the corresponding empirical values. We cannot yet explain the origin of the discrepancy, but we suspect that it relates to differences in the measurement of CSFs in the two studies. Specifically, the CSFs for the amblyopes in the present study were measured with Gabor patches rather than full-field sine-wave gratings, as was the case for Chung et al. (in press). For CSF measurement, the size of the stimuli may have a bearing on probability summation, which could lead to a difference in shape in the CSFs, especially at the low spatial frequency end of the CSF. We also note that the amblyopic CSFs were measured approximately two years prior to the collection of the letter identification data reported in this paper.² However, we have no reason to suspect that these CSFs would have changed significantly during that period.

As noted in the Introduction, amblyopes have reduced efficiency in identifying small letters (Levi et al., unpublished data). According to Levi et al., a reduced efficiency could result from weak or unreliable central connections, or an abnormally wide integration area in the amblyopic visual system. Our findings suggest that the reduced efficiency is *not* a consequence of abnormal “channel” properties. Rather, we found that the spatial-frequency properties of letter identification are similar between the amblyopic and the non-amblyopic eyes, differing only by a scale factor, the acuity. Apparently, the visual deficits in amblyopes, which usually develop early in life, do not have any impact on the spatial-frequency properties associated with letter identification. The deficit is only exhibited as a difference in the range of “channels” for letter identification.

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² The CSF-ideal-observer analysis emerged following data collection, so measurement of CSFs was not included in the experimental design of the present study.

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