Sampling limits and critical bandwidth for letter discrimination in peripheral vision

Roger S. Anderson* **and Larry N. Thibos**

Visual Sciences Group, School of Optometry, Indiana University, Bloomington, Indiana 47405

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We develop and test two functional hypotheses based on the sampling theory of visual resolution that might account for letter acuity in peripheral vision. First, a letter smaller than the acuity limit provides insufficient veridical energy for performing the task, and, second, the available veridical energy is masked by increased amounts of visible but aliased energy. These two hypotheses make opposite predictions about the effect of low-pass filtering on letter acuity, which we tested experimentally by using filtered letters from the tumbling-E alphabet. Our results reject the masking hypothesis in favor of the energy insufficiency hypothesis. Additional experiments in which high-pass-filtered letters were used permitted the isolation of a critical band of spatial frequencies, which is necessary and sufficient for achieving maximum visual acuity. This critical band varied with the particular pair of letters to be discriminated but was in the range 0.9–2.2 cycles per letter.

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1. INTRODUCTION

Letter acuity is the chief measure of visual performance in clinical settings, yet visual science currently lacks a comprehensive account of the mechanisms that limit acuity. Part of the challenge is to account for the complexity of the stimulus as well as the paradigm. In contrast to the simplicity of sinusoidal grating stimuli, alphanumeric letters have rich Fourier spectra that cover a broad range of spatial frequencies, orientations, and phases. Furthermore, as letters are reduced in size their spectra expand into the domain of higher spatial frequencies because of the inverse relationship between spatial dimensions and retinal frequency, expressed in cycles per degree. As the spectrum expands, the higher-frequency components will be the first to cross physiological barriers to legibility (e.g., the optical cutoff of the eye's optical system), thus leaving only the lower frequencies to support psychophysical performance. As the letter is reduced in size, the available stimulus energy in these lower spatial frequencies declines and eventually becomes insufficient to support the visual task, and so the acuity limit is attained. Thus the acuity paradigm, by its very nature, converges on the lowest-frequency components that have sufficient energy to support letter discrimination. Experimental studies have shown that this critical band of object frequencies is in the range 1–2 cycles per letter (c/let) for foveal vision,[1–6] although the results depend somewhat on the choice of letters in the test alphabet.[7]

In peripheral vision, accounting for letter acuity is further complicated by the relatively low neural sampling limit of the peripheral retina compared with the eye's optical cutoff frequency. The latter determines the highest spatial frequency that can appear in the retinal image, whereas the former determines the highest spatial frequency that can be represented veridically in the neural image after the retinal image is sampled by the array of retinal receptive fields. In central vision, the optical cutoff frequency of the typical eye is lower than the neural Nyquist limit,[8] and therefore the retinal image is always adequately sampled. However, in peripheral vision the optical bandwidth of the well-focused eye greatly exceeds the Nyquist limit,[9,10] and therefore the retinal image is subject to neural undersampling, which causes misrepresentation of the stimulus. The result is a type of spatial misperception called aliasing that prevents the resolution of fine spatial patterns.[11] The onset of aliasing is a reliable measure of grating acuity because it marks the sharp transition from veridical to nonveridical perception of spatial structure, which takes place as the grating's frequency crosses the Nyquist boundary.[12] However, for stimuli with rich Fourier spectra, such as letters, the situation is complicated by a mutual masking interaction in which components below the Nyquist frequency mask the visibility of supra-Nyquist aliasing[13] and vice versa.[14] This masking is partially responsible for the observation that aliasing of higher harmonics is not perceived for high-contrast square-wave gratings in the periphery,[15] and presumably the same is true for harmonics of the characteristic frequency of letters. Nevertheless, it is possible that other undersampled components in the rich spectra of letters might hamper resolution by masking those veridical, sub-Nyquist components that are needed for letter discrimination.

Our objective for the present study was to assess the relative importance of the two mechanisms identified above in determining the acuity limit of human observers for identifying letters in peripheral vision. In keeping with the terminology of the companion paper,[16] we refer to the notion of insufficient veridical signal energy to support visual resolution as the energy insufficiency hypothesis. Likewise, we refer to the active masking of essential sub-Nyquist components by undersampled, supra-Nyquist components as the masking hypothesis. Because the dual effects of reduced veridical energy and

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active masking by nonveridical energy are both consequences of undersampling, we use the overarching term sampling-limited to mean that either, or both, of these two effects is the main factor that limits performance on a visual task.

2. EXPERIMENTAL RATIONALE

The companion paper of Anderson and Thibos[16] provided a framework for investigating the effects of undersampling and masking in peripheral vision based on the sampling theory of visual resolution.[17] According to this model, which is illustrated in Fig. 1, two letters may be reduced in size and can still be discriminated, provided that critical frequency components that distinguish the two stimuli fall below the Nyquist limit. To help to identify these distinguishing frequency components we compute a difference spectrum by subtracting the complex-valued spectra (in order to retain phase information) of the two letters being discriminated. In this two-dimensional spectral domain of retinal images, the locus of the Nyquist limit is a circle centered on the origin with its radius equal to the Nyquist frequency. (A more accurate depiction of the Nyquist limit would stretch the circular ring into an ellipse to take account of the spatial anisotropy of the retina[18–20] and make it a fuzzy border to account for irregularity in the sampling mosaic,[14,21] but those refinements were not implemented here.) This circle, which we call the Nyquist ring, partitions the spatial-frequency spectrum into an inner domain of adequately sampled, veridically represented components and an outer domain of undersampled, aliased components. If letter size is reduced sufficiently, a significant amount of stimulus energy moves from the veridical domain to the aliasing domain, as shown by the cartoon in Fig. 1(b). This transfer of energy across the Nyquist boundary has two deleterious consequences: (1) there is less veridical energy inside the ring to support the task of letter discrimination and (2) the remaining veridical energy inside the ring is subjected to masking by the increased amount of aliased energy outside the ring.

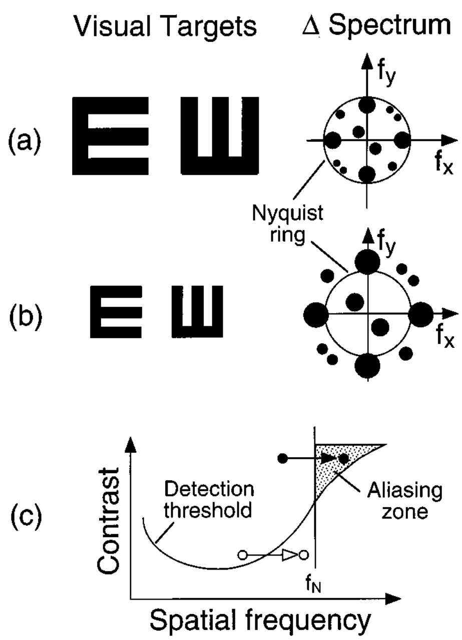

Fig. 1. Peripheral-vision model of visual acuity based on the difference in Fourier spectra of letters to be discriminated. (a) At the acuity limit, critical frequency components in the difference spectrum lie just inside the Nyquist ring. (b) As letters shrink below the acuity limit, the Fourier spectrum expands, causing stimulus energy to escape the Nyquist ring. This prevents letter discrimination for either of two possible reasons: (1) there is insufficient veridical energy available to support the discrimination task or (2) signal energy outside the Nyquist ring is undersampled, which produces aliasing that can mask the visibility of remaining veridical components inside the Nyquist ring. (c) A shrinking target causes individual frequency components to shift to higher spatial frequencies, which will lead to contrast insufficiency when the component crosses the Nyquist boundary (filled symbols) or when it crosses the threshold for contrast detection (open symbols).

The experimental design of the companion paper[16] was inadequate to permit us to determine whether the loss of veridical energy as a result of undersampling is more or less important for determining visual acuity than is increased masking by aliased energy. In the present study we aimed to rectify this shortcoming by using letter targets that were spatially filtered to eliminate those higher frequencies that are destined to escape the Nyquist ring first as the letter shrinks in size. If the normal acuity limit for unfiltered letters is determined primarily by the masking effect of undersampled high-frequency components, then this limitation should be removed by low-pass filtering. The result would be that letters could be reduced in size below the normal acuity limit and still be discriminable. Thus the masking hypothesis predicts supernormal visual acuity when the high-frequency components of letters are attenuated by a low-pass filter.

A different prediction arises under the alternative hypothesis that normal acuity for unfiltered letters is determined primarily by insufficient energy in the veridical band of frequencies below the Nyquist limit. As illustrated in Fig. 1(c), some frequency components may escape the Nyquist ring into the aliasing zone as the letter shrinks, and other components that remain inside the Nyquist ring may fall below visual threshold when they shift to higher frequencies. In either case, low-pass filtering of letters would do nothing to restore these losses of veridical energy as a letter shrinks in size. Therefore the energy-insufficiency hypothesis predicts that acuity will not improve with filtering.

Our primary aim in making this study was to test the two hypotheses given above by experimentally evaluating their predictions. A secondary aim was to delineate the critical band of spatial frequencies that determines letter acuity in the periphery. Both hypotheses predict that low-pass filtering will reduce acuity when insufficient signal energy is passed by the filter. Thus the low-pass filtering paradigm may be used to quantify the upper limit to that low-frequency spectrum that is sufficient to support letter discrimination at the normally acuity end point. In a a complementary experiment we used high-pass filtering to determine whether very low frequencies (<1.5 c/let) can be removed without affecting acuity. The rationale for both of these experiments was that if filtering has no effect on acuity, then the attenuated components were unnecessary for performing the task. In this way we hoped to isolate that critical band of frequencies that, if present, is capable of supporting the same level of visual acuity as for unfiltered letters but, if absent, would lead to significant loss of acuity.

3. METHODS

We prepared visual targets by spatially filtering the same long- and short-stroke tumbling-E characters described in the companion study.[16] Characters were low-pass filtered at six different cutoff frequencies (2.5, 2.2, 1.9, 1.6, 1.25, and 0.9 c/let). Spatial filtering of each letter was done by computer, which performed a finite Fourier transform on the image to produce the complex spectrum of the original letter. Spatial resolution of this discrete spectrum was 0.3125 c/let. For low-pass filtering, this spectrum was multiplied by a circular window centered on zero with a radius equal to the desired cutoff frequency. An example is shown in Fig. 2. We define the characteristic frequency of a letter to be the fundamental frequency of that square wave that has a half-period equal to the stroke width of the letter. Spectral dispersion caused by truncation of an extended square wave to form the letter E causes energy in the fundamental harmonic to disperse into a band of frequencies centered on the characteristic frequency, as may be seen from Fig. 2.

Our low-pass filter had values of unity inside the window and zero outside, so all frequency components equal to or less than the cutoff value were retained. An inverse finite Fourier transform was then performed on the filtered spectrum to produce the experimental stimulus. The appearances of some of these differently filtered letters are as shown in Fig. 3. Because mathematical low-pass filtering can yield negative intensity values for letters of 100% contrast, the contrast of unfiltered letters ($\Delta I/I$) was set at 85% so that after filtering all intensity values were nonnegative. High-pass letters were produced by the same method with the same six cutoff frequencies, except that the filter had value zero for frequencies less than or equal to the cutoff and of unity for frequencies greater than cutoff. The appearances of some of these letters are shown in Fig. 4.

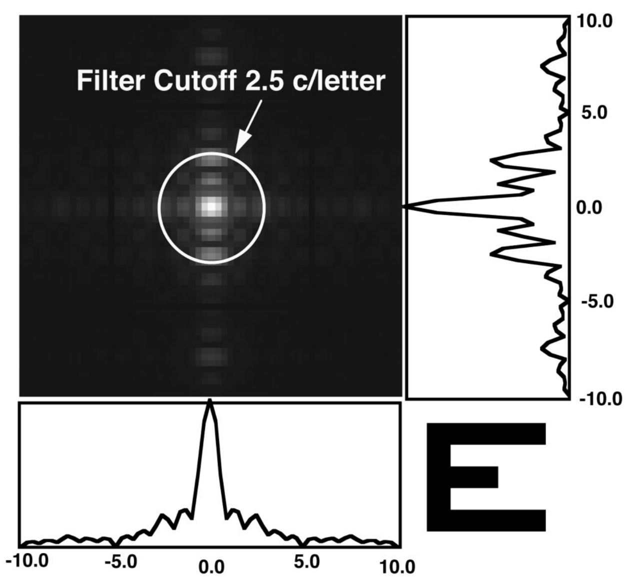

Fig. 2. Amplitude spectrum of a short-stroke E. The circular window shows the filter cutoff frequency. Frequencies outside the window were removed to low-pass filter, and frequencies within the window were removed to high-pass filter.

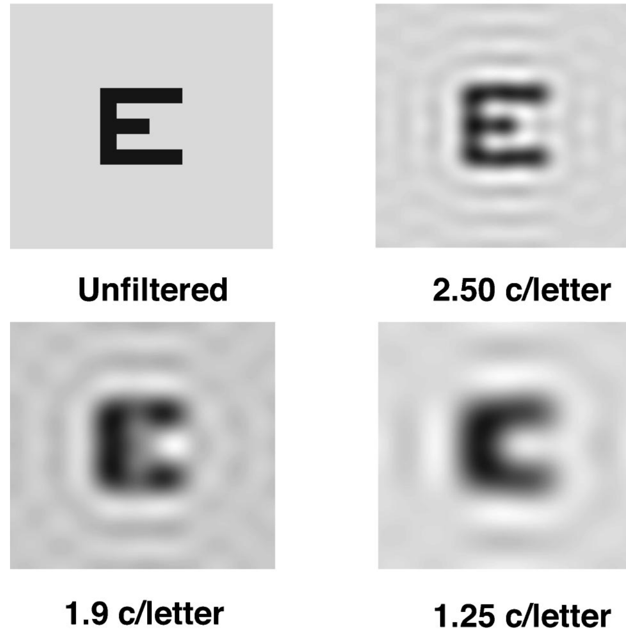

Fig. 3. Appearance of a short-stroke E, unfiltered and low-pass filtered at different cutoff frequencies.

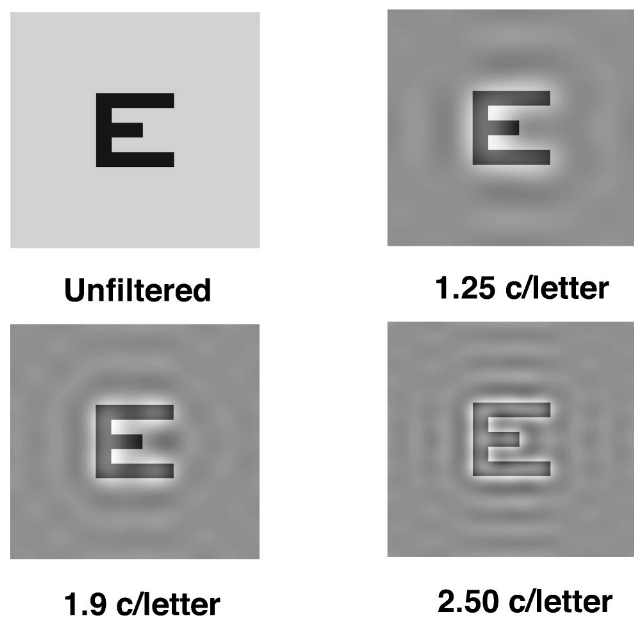

Fig. 4. Appearance of a short-stroke E, unfiltered and high-pass filtered at different cutoff frequencies.

Targets were presented 30 deg into the horizontal, temporal field, and the subject's task was to identify the orientation of the letter from two possible alternatives [right versus up (R vs. U) or right versus left (R vs. L)]. Visual acuity, defined as the minimum letter size that permitted reliable performance on this task, was determined by a staircase procedure. Further details of the experimental method are described in the companion paper.[16]

4. RESULTS

A. Low-Pass Filtering

The dependence of letter acuity on the cutoff frequency of the low-pass-filtered, long-stroke E's are shown in Fig. 5. The inset images illustrate the difference spectra of the filtered targets to be discriminated following various degrees of filtering. One can determine the calibration of the frequency axes of these spectra by noting that the gap between the low-frequency core and the band of energy surrounding the characteristic frequency occurs at 1.25 c/let in the unfiltered R vs. U spectrum, which is half of the characteristic frequency. Our 2.5-c/let low-pass filter removed all the stimulus energy above the characteristic frequency, including a portion of the prominent band of frequencies centered on the characteristic frequency.

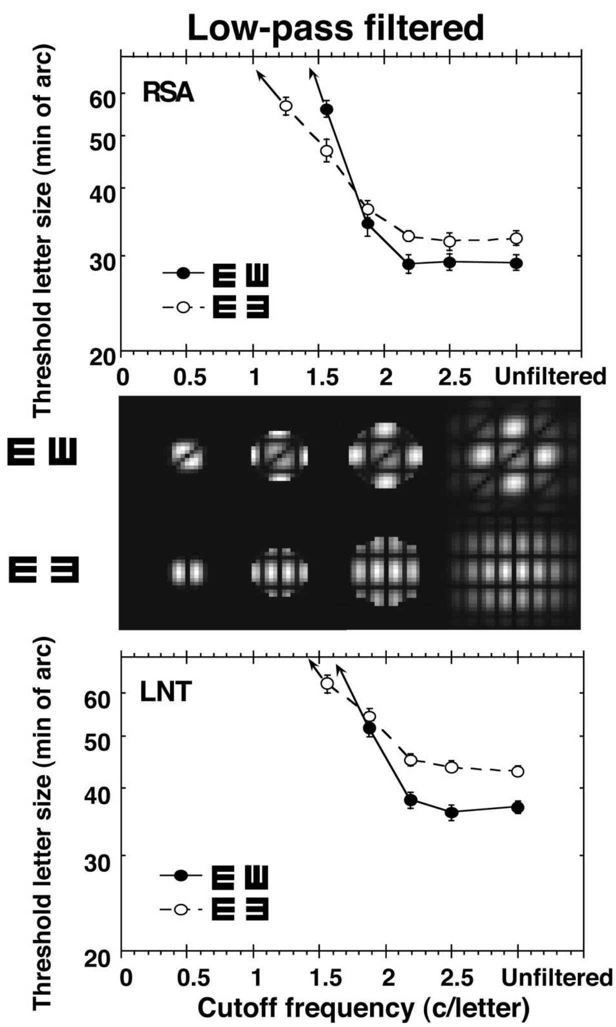

Fig. 5. Threshold letter size versus cutoff frequency for long-stroke E's that were low-pass filtered at different cutoff frequencies. Symbols show the means of two settings, and error bars represent one standard deviation of two threshold measures. The standard deviation of the staircase reversal values on any given run averaged ~10% of the mean. Arrows indicate that the subject was unable to identify even the largest letter (80 arc min) that could be displayed on the computer monitor. Inset, difference spectra for the R vs. U configuration (upper row of spectra) and the R vs. L configuration (lower row). Cutoff frequencies represented by the four difference spectra (from left to right) are 1.25, 1.9, and 2.5 c/let and unfiltered. Labels "RSA" and "LNT" identify the observers here and in subsequent figures.

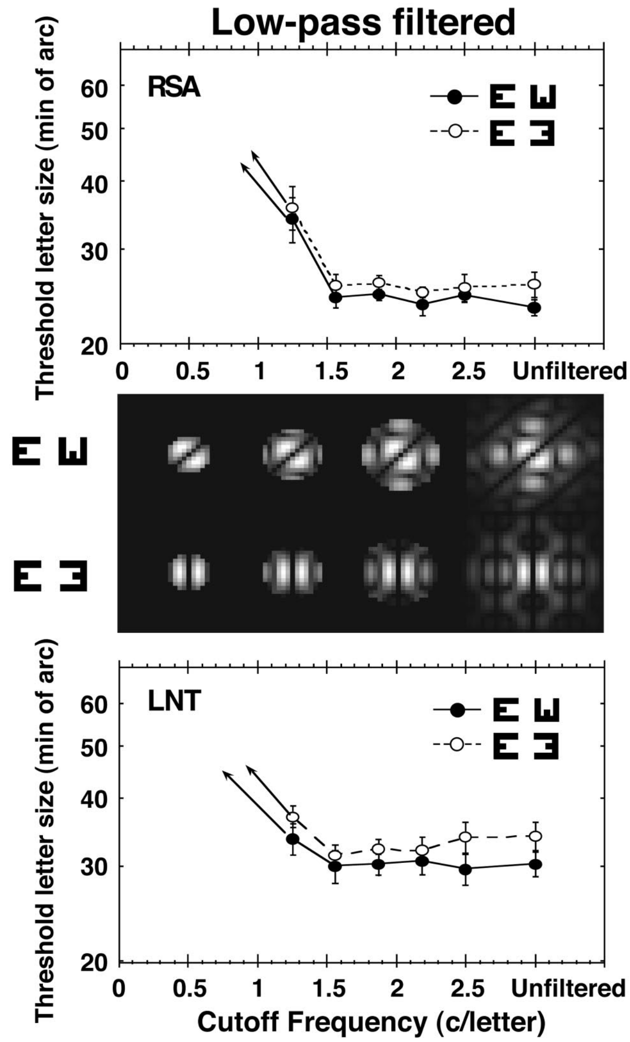

Fig. 6. Threshold letter size versus cutoff frequency for short-stroke E's that were low-pass filtered at different cutoff frequencies. The middle panel in Figs. 6–8 illustrates the difference spectra for the R vs. U configuration (upper row of spectra) and the R. vs. L configuration (lower row). Cutoff frequencies represented by the four difference spectra (from left to right) are 1.25, 1.9, and 2.5 c/let and unfiltered.

Nevertheless, our subjects performed as well for this stimulus as for the unfiltered letter. Similarly, performance was not hampered significantly when the cutoff frequency was reduced to 2.2 c/let, an operation that removed a significant amount of energy in the characteristic frequency band. The first measurable effect of low-pass filtering on acuity occurred when the filter cutoff was 1.9 c/let, which eliminated a majority of the energy in the characteristic frequency band. In this case the minimum letter size required by subjects to discriminate the targets increased significantly. Acuity continued to decline as the cutoff frequency of the filter was reduced, until eventually subjects were unable to perform the task even for the largest target that could be presented on our computer monitor. This pattern of results leads us to reject the masking hypothesis in favor of the energy insufficiency hypothesis as formulated above.

The same conclusion may be drawn also for the experiment that requires discrimination of R vs. L filtered letters, as shown in Fig. 5. Although unfiltered acuity is significantly worse for this target pair than for R vs. U, performance does not change significantly when the stimulus is filtered with the 2.5- or 2.2-c/let filter. One of the surprising features of the data in Fig. 5 is that the curves intersect at ~1.6 c/let, indicating that acuity for discriminating R vs. L letters actually exceeds acuity for discriminating R vs. U letters when the letters are strongly filtered. We return to this point in Section 5.

For short-stroke letter pairs (Fig. 6), the cutoff frequency of the low-pass filter could be reduced even further than for long-stroke letters before acuity became affected. For both discrimination tasks (R vs. U and R vs. L), acuity was unaffected for cutoff frequencies of 1.6 c/let or greater, compared with 2.2 c/let for the long-stroke letters. This result highlights the fact that the effect of filtering on letter discrimination depends on the particular choice of letters being discriminated. Inspection of the difference spectra for these two letter pairs indicates that the 1.6-c/let filter completely removed the band of energy surrounding the characteristic frequency, leaving only the low-frequency core. This result proves that the characteristic frequency components of the short-stroke E are not necessary for discriminating the orientation of the short-stroke letter. Given the appearance of the test target (Fig. 3), it is not surprising that the orientation of the short-stroke letters could be discriminated equally well with or without filtering at 1.6 c/let. Because acuity did not improve with low-pass filtering, we again reject the masking hypothesis in favor of the energy insufficiency hypothesis.

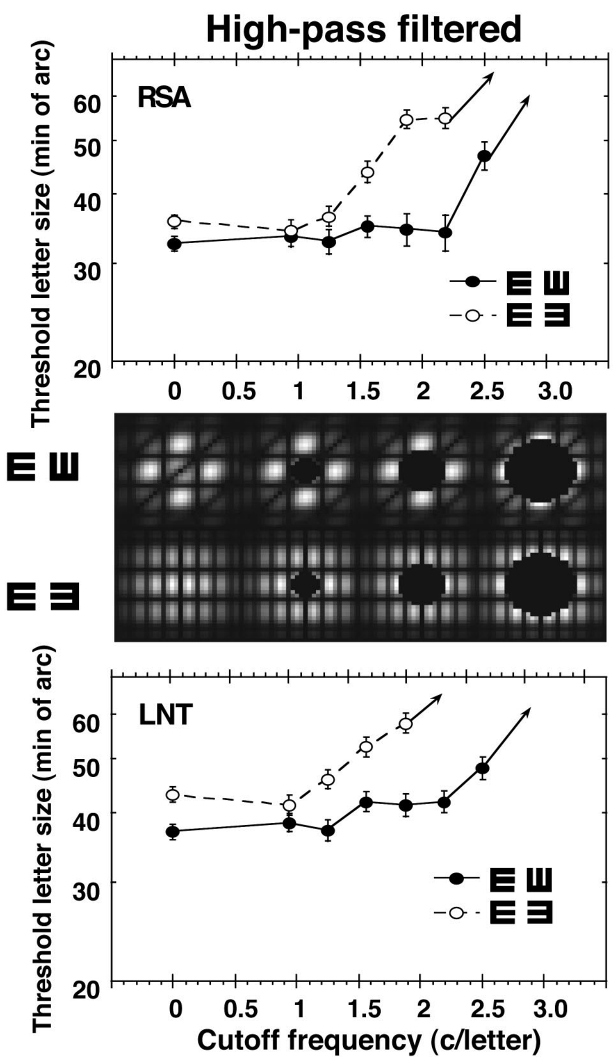

Fig. 7. Threshold letter size versus cutoff frequency for long-stroke E's that were high-pass filtered at different cutoff frequencies. Cutoff frequencies represented by the four difference spectra (from left to right) are unfiltered and 0.9, 1.6, and 2.5 c/let.

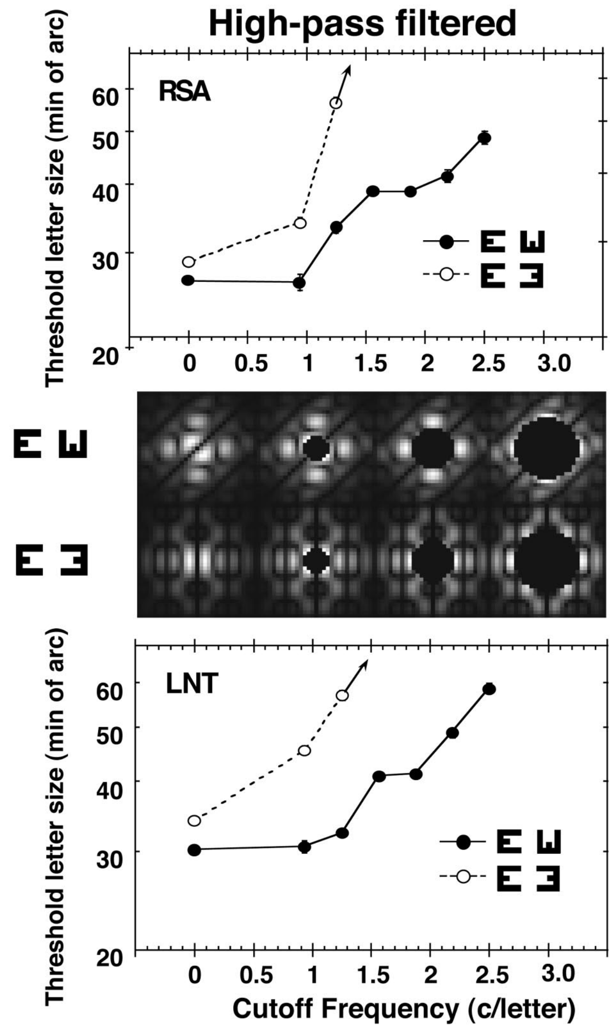

Fig. 8. Threshold letter size versus cutoff frequency for short-stroke E's that were high-pass filtered at different cutoff frequencies. Cutoff frequencies represented by the four difference spectra (from left to right) are unfiltered and 0.9, 1.6, and 2.5 c/let.

B. High-Pass Filtering

The dependence of letter acuity on the cutoff frequency of the high-pass-filtered, long-stroke E's is shown in Fig. 7. These results indicate that frequency components up to and including 2.2 c/let could be removed without affecting acuity for the R vs. U discrimination. However, for the R vs. L discrimination only the components up to 1.25 c/let could be removed without affecting acuity. For any given cutoff frequency, acuity was always better for R vs. U discrimination than for R vs. L. Surprisingly, the R vs. U discrimination was still possible despite the removal of all frequency components equal to or less than the characteristic frequency with the 2.5-c/let filter. However, the task could not be performed by either subject for the R vs. L discrimination task when the stimulus was high-pass filtered with the 2.5-c/let cutoff.

High-pass filtering had a much stronger effect on discrimination of short-stroke letters (Fig. 8) than of long-stoke letters (Fig. 7). This was especially true for discriminating R vs. L letters, in which case even the smallest amount of filtering (0.9-c/let cutoff) reduced acuity. These results emphasize the importance of the low-frequency components for discriminating the short-stroke letters.

5. DISCUSSION

Our masking hypothesis predicted that removal of the higher-spatial-frequency components of letters by low-pass filtering will defeat the mechanism that normally limits peripheral acuity and thereby elicit supernormal acuity. This prediction was not verified (Figs. 5 and 6) for either subject, either task, or either letter font. Therefore we reject the hypothesis that masking of veridical components of tumbling-E letters by undersampled components is the mechanism that limits peripheral visual acuity.

The alternative hypothesis, that acuity is limited by insufficient veridical energy in those frequency components that lie below the neural Nyquist limit, predicts that low-pass filtering will never improve acuity; it can only reduce acuity. This hypothesis is consistent with the results of Figs. 5 and 6 and allows us to account for the acuity limit in peripheral vision as follows: As a letter is reduced in size, its spatial-frequency spectrum expands and in the process expels signal energy from the veridical domain inside the Nyquist ring to the aliasing domain outside the Nyquist ring. Surprisingly, this loss of veridical energy can be quite severe without loss of acuity. For example, when one is discriminating the R vs. U long-stroke E's, all the energy above 2.2 c/let may be eliminated, leaving just a small portion of that band of frequencies near the characteristic frequency, without affecting acuity (Fig. 5). This suggests that these high-contrast letters have a large reserve of energy near the characteristic frequency, which makes their discrimination possible even in the presence of severe filtering. Even more surprisingly, all the energy above 1.6 c/let, which includes the entire band of frequencies near the characteristic frequency, may be eliminated from the short-stroke E's without affecting acuity for orientation discrimination (Fig. 6). This result highlights the importance of even minor changes in the structure of a letter on the letter's Fourier spectrum. Evidently, removing one half of one stroke of a letter introduces new spatial-frequency components that can improve letter discrimination. Nevertheless, if the letters are made small enough there will come a point where an insufficient amount of veridical energy in the difference spectrum remains inside the Nyquist ring to support the discrimination task. This is the acuity limit.

When letters that are normally just resolvable are filtered sufficiently to prevent reliable discrimination, we find that we can regain performance of the discrimination task by enlarging the filtered stimulus. This result is interpreted by the experimenter as a loss of acuity, but it is not obvious why performance of the task may be restored simply by rescaling the stimulus. If the filtering operation had removed certain necessary components of the letter's spectrum, then rescaling would not restore performance because rescaling cannot restore the lost components.[22] Indeed, this result appears to explain the inability of our subjects to discriminate strongly filtered letters regardless of their size (Figs. 5–8). The unexplained behavior, then, is for moderate levels of filtering for which performance is still possible but subnormal. In this case we presume that the remaining veridical components of the letter's spectrum would be sufficient for the discrimination task if only they were visible, but at the normal acuity limit they fall below visual threshold. Enlarging the letter causes the spatial frequencies of these components to decline, thus allowing signals to cross the border from invisible to visible, as shown schematically in Fig. 1(c). In this way frequency components attenuated to a subthreshold level by filtering are rendered visible again by shifts of their frequencies to lower values where contrast sensitivity is higher. In this way lost components are regained for supporting the psychophysical task by spatial scaling of the letter.

Although much of the energy near the characteristic frequency of letters may be eliminated without affecting acuity, thus demonstrating that these components are unnecessary for maximizing visual resolution, they may nevertheless be sufficient for discriminating high-pass filtered letters. Figure 7 shows that when the long-stroke E's are high-pass filtered at 2.5 c/let, only a small portion of the characteristic band of frequencies remains. These components will be undersampled when the letter is at the normal acuity limit, which explains why the letters cannot be discriminated. However, if the letters are magnified slightly, their spectra will contract, so the residual energy in the characteristic frequency band will be drawn back into the veridical zone inside the Nyquist ring. Evidently this small amount of veridical energy is sufficient to permit subjects to perform the task, albeit at a slightly reduced acuity level.

The energy insufficiency hypothesis may also explain the crossover in performance that is evident in Fig. 5, in which R vs. L acuity exceeds R vs. U acuity for severely filtered letters. For unfiltered letters there is 40% more energy in the R vs. U difference spectrum than in the R vs. L spectrum, which is consistent with higher acuity for R vs. U. However, just the opposite is true for cutoff frequencies less than or equal to 1.6 c/let. For example, for the 1.6-c/let filter there is 20% more energy in the R vs. L difference spectrum. This reversal in the relative amounts of signal energy with filtering does not occur for the short-stroke characters, an outcome that is consistent with the superiority of R vs. U performance at all cutoff frequencies.

A. Critical Bandwidth for Letter Discrimination

Figure 9 summarizes the effect of high- and low-pass filtering on the discrimination of long-stroke E's in the periphery. Symbols show the mean acuity of our two sub-

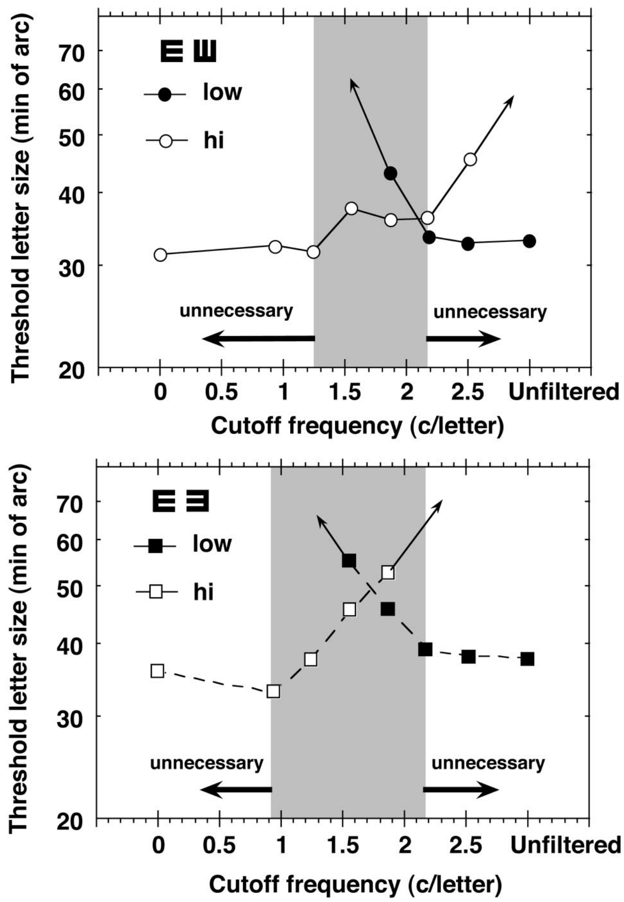

Fig. 9. Threshold letter size versus cutoff frequency for long-stroke E's that were low-pass and high-pass filtered at several cutoff frequencies (mean of both subjects). Shaded areas indicate the bands of frequencies that are necessary and sufficient for supporting normal visual acuity at the test location.

jects for discriminating R vs. U and R vs. L orientations. The shaded areas indicate critical bands of spatial-frequency components that are both necessary and sufficient for attaining normal acuity. The critical band is 1.25–2.25 c/let for R vs. U letters and 0.9–2.25 c/let for R vs. L letters. We claim that these frequency components are necessary because acuity suffers if they are removed by either high-pass or low-pass filtering. We claim that these components are sufficient for attaining normal acuity levels based on one further experiment conducted on subject RSA with R vs. U long-stroke letters that had been bandpass filtered at 1.25–2.2 c/let. Threshold letter size for this letter pair was 31.4 arc min, which was not significantly different from that obtained for the unfiltered characters (28.7 arc min), thus confirming that the specified band of frequencies is sufficient for attaining normal acuity.

The summary of our results for short-stroke letters is shown in Fig. 10. For this letter pair the critical band of frequencies was found to lie at 0.9–1.6 c/let for R vs. U letters and 0–1.6 c/let for R vs. L letters. We tested the sufficiency of this band of frequencies with R vs. U short-stroke letters filtered with the corresponding bandpass filter. Threshold letter size was 24.5 arc min, which was not significantly different from that obtained for the unfiltered characters (23.1 arc min).

Our measurements of the critical bandwidth for letter discrimination in the peripheral field are in broad agreement with the literature on foveal vision[1,2,4] and peripheral vision,[6] showing that it is the lower object frequency components that are important in letter discrimination. Our results also show that the critical band of frequencies for letter discrimination depends on the particular letter pair being discriminated.

B. Is Letter Acuity Sampling-Limited?

When taken in conjunction with the results of the companion study,[16] the present results allow us to answer the original question that motivated this work: Is letter acuity sampling-limited in the periphery? The meaning of the phrase "sampling-limited" is illustrated in Fig. 1(c). As a letter shrinks, its spectrum expands, forcing high-contrast components of a letter to cross the Nyquist boundary into the aliasing zone (filled circles), thus depriving the observer of veridical information. In principle, that aliased energy might exert a secondary masking effect on sub-Nyquist components, but the present results have dismissed that possibility for the E letter targets. At the same time, important low-frequency components may fall below threshold for detection before they reach the Nyquist limit (open circles). Although both

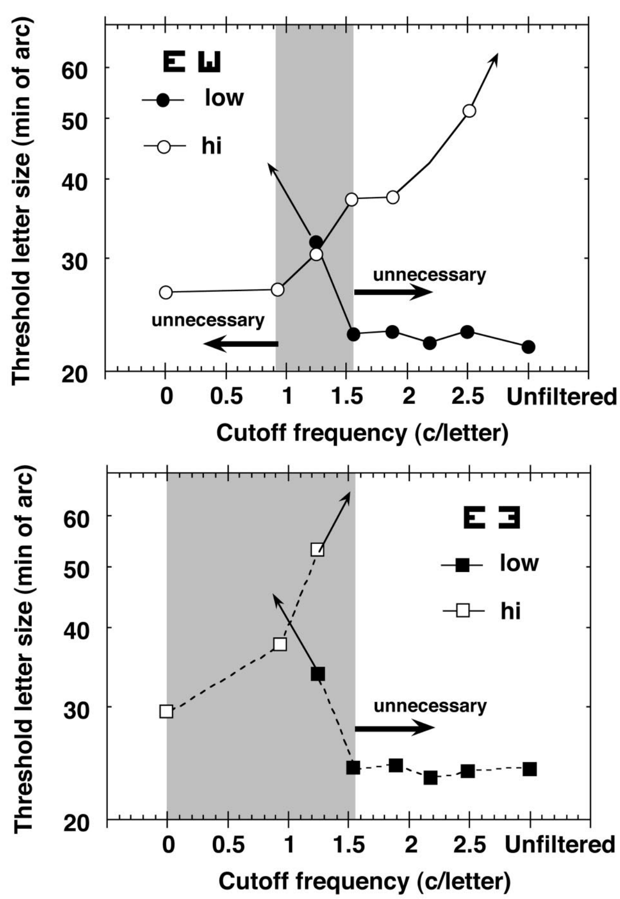

Fig. 10. Threshold letter size versus cutoff frequency for short-stroke E's that were low-pass and high-pass filtered at different cutoff frequencies (mean of both subjects). Shaded areas indicate the band of frequencies that are necessary and sufficient for supporting normal visual acuity at the test location.

situations represent examples of energy insufficiency that could limit acuity, only the first invokes a sampling mechanism for which the term sampling-limited is justified.

With this understanding of terminology, the discrimination of long-stroke letters E in the R vs. U configuration is the only task in the present study for which we have evidence that performance is limited by neural sampling of the retinal image. Discrimination of this letter pair qualifies as a sampling-limited task for two reasons: First, the critical band of frequencies required by observers to distinguish this letter pair (Fig. 9) closely matches the prominent band of frequencies centered on the characteristic frequency (Fig. 7) and lies just below the Nyquist frequency at the acuity end point (see Fig. 7 of the companion paper[16]). Second, the measured acuity for this letter pair is the same as the acuity for three-bar square-wave gratings[16] and for sinusoidal gratings truncated to 2.5 cycles.[23] The sampling-limited nature of the latter task is strongly supported by the additional observations of subjective aliasing and of the fact that detection acuity exceeds resolution acuity. As for the other letter pairs tested here, the critical bandwidth of R vs. L long-stroke E's is too broad to fit neatly into an undersampling model. Subjects clearly depend on the low object frequencies to do the task, and those frequencies are far from the Nyquist limit at the acuity end point. Similarly for the short-stroke E's, the critical band is well below the Nyquist frequency at the acuity end point, so we have no reason to suppose that they are being undersampled. Given that even minor changes in a letter's structure, such as reducing the length of a single stroke in the letter E, can prevent performance from reaching the limits set by neural sampling, it seems unlikely that discrimination of other letter pairs from the alphabet will achieve sampling-limited performance.

C. Importance of Spatial Phase

Several lines of evidence suggest that visual performance for discriminating patterns with rich Fourier spectra is hampered in peripheral vision by deficiencies in the encoding of spatial phase.[24–26] Our study was not designed to test these ideas, and our results are not incompatible with that viewpoint. Our experiments were conceived in the context of the known sampling limitations of peripheral vision and were aimed at determining whether the end point of an acuity experiment is set by the loss of veridical information or by the gain of unwanted masking due to neural undersampling. Our findings in favor of the energy insufficiency hypothesis should not be construed as evidence against the importance of spatial phase information. Spatial phase information is thought to be encoded by the relative responses of orthogonal pairs of visual receptive fields that have even and odd symmetry.[24] Such responses will not occur in the absence of stimulus contrast, and therefore the detection of stimulus contrast is a necessary precursor to phase encoding. We have developed the difference spectrum concept as a tool to identify those spatial-frequency components that differ enough between the two targets to form a basis for the visual discrimination of the targets, whether by phase-sensitive mechanisms or by any other scheme that may exist in the visual system.

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*Present address; Vision Science Research Group, School of Biomedical Sciences, University of Ulster at Coleraine, County Londonderry, Northern Ireland, UK.

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