No Aliasing at Edges in Normal Viewing
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Although spatial aliasing by the extrafoveal retina can occur under natural viewing conditions, it does not commonly disturb our vision. One possible explanation for this is that real scenes do not have sufficient power in the high frequencies to produce aliasing. We examined whether aliasing distorted the appearance of a high contrast edge, which is a common stimulus in the environment. Observers made a two-interval forced-choice discrimination between low-pass filtered and unfiltered edges at 0, 10, 20, and 40 deg eccentricity. This discrimination could be made only when frequency components were removed below both the cone and ganglion cell Nyquist frequencies at each eccentricity. Since supra-Nyquist frequency components could not be detected in edges, they are incapable of producing aliasing.

Aliasing Sampling Edges Retina Peripheral vision

INTRODUCTION
Aliasing occurs when interference fringes of sufficiently high spatial frequency are imaged on the cone mosaic (Thibos, Cheney & Walsh, 1987; Thibos, Walsh & Cheney, 1987; Williams, 1985, 1986, 1988; for a recent review, see Williams, 1992). The fact that these effects are not apparent during normal viewing is explained, in the case of the fovea, by the near match between the Nyquist frequency for the photoreceptor array and the highest frequency that the optics of the eye will pass (Snyder & Miller, 1977). In the near periphery, however, the relatively high quality of the optics (Jennings & Charman, 1981; Artal, Navarro, Brainard, Galvin & Williams, 1992) and the drastic fall-off in cell density causes the retina to undersample (Yellott, 1982). High contrast, high frequency gratings presented on a CRT will produce aliasing artifacts in the periphery. Smith and Cass (1987a) showed a discrepancy between detection and orientation resolution thresholds which they attributed to aliasing. Smith and Cass (1987b) and Anderson and Hess (1990) have shown that the motion reversal effect, seen by Coletta, Williams and Tiana (1990) using drifting interference fringes, can also be obtained with conventional gratings. Williams, Sekiguchi, Haake, Brainard and Packer (1991) have demonstrated the existence of aliasing by submosaics of S, L, and M cones in natural viewing.

Since it is possible to see aliasing under normal viewing conditions, we wish to clarify why we are not more frequently aware of this image distortion. It is true that the high contrast, high spatial frequency gratings usually used to elicit aliasing are rare in our environment (Bosomaier, Snyder & Hughes, 1985; Snyder, Bosomaier & Hughes, 1986). The spatial frequency spectra of natural scenes are continuous with a fall-off in amplitude that is roughly inversely proportional to spatial frequency (Field, 1987; Burton & Moorehead, 1987). One possibility, then, is that natural scenes do not have enough contrast at high frequencies to produce aliasing artifacts. These spectra are far fields and are averaged over all orientations however, so it could still be the case that local regions of the field could contain features susceptible to aliasing.

One experimental approach to the question of whether extrafoveal aliasing occurs in natural scenes would involve asking observers to discriminate between natural scenes and filtered versions of the same scenes that lack spatial frequencies in the aliasing range. If observers were unable to make such discriminations then there could be no aliasing artifacts available as a cue. Unfortunately, such an experiment would involve a large number of natural scenes, and these would need to be recorded and displayed without distortion. We have chosen a simpler approach based on knowledge about the kinds of features in real scenes that are likely to produce aliasing. In general, patterns that produce aliasing are those that change rapidly on the spatial scale of the spacing between sampling elements. Edges have this property and are frequently present in real scenes. They also have spectra which fall off as the inverse of spatial frequency. Furthermore, it is well known that edges are a potential source of local aliasing in computer graphics displays.

Figure 1 gives an example of aliasing at an edge. We have sampled the edge in Fig. 1(B) with the cone array from the peripheral retina of a macaque (supplied by Hugh Perry) shown in Fig. 1(A). We then used linear interpolation to produce the reconstructed image shown

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FIGURE 1. A simple edge (A) sampled by a digitized macaque cone array (B) is shown reconstructed using a linear interpolation algorithm in (C). The same edge with spatial frequencies above the Nyquist limit for the sampling array (about 17 cycles per picture width) removed is shown in (D), and is sampled and reconstructed as before (E). The distortion is further reduced if all the frequencies above half the Nyquist limit are removed from the original, as in (F), which is reconstructed as (G).

in Fig. 1(C). The ragged boundary is one possible alias for the edge, since its values at the sample points are all exactly the same as those of the edge. However, this distortion can be reduced just by removing high frequencies from the edge before sampling it. Figure 1(D) shows the edge in Fig. 1(B) but with frequencies above the
nominal Nyquist frequency removed. We define the nominal Nyquist frequency for the mosaic to be that of a regular, triangular mosaic with the same mean density (Coletta & Williams, 1987). Figure 1(E) shows the sampled and reconstructed version of this filtered edge. Removing the high frequencies down to half the Nyquist frequency [Fig. 1(F)] results in only a little distortion after sampling and reconstruction [Fig. 1(G)].

In this paper we have asked whether these high frequencies in edges that could produce aliasing are actually detectable. We removed the high spatial frequencies from edges and found that these filtered edges could not be discriminated from perfect, unfiltered ones unless frequency components were removed below the cone and ganglion cell Nyquist frequencies. This shows that spatial frequency components of edges above the Nyquist frequency of the sparsest retinal sampling array are not detectable, and therefore the retina does not produce visible aliasing distortion of edges.

We also tested for aliasing at narrow lines, as they are another common feature with an abrupt luminance change, but have a flat rather than declining spectrum. We were interested to know whether having energy at high frequencies is enough to produce aliasing, or if it is necessary to have a repetitive pattern in which a disturbance can be seen. The outcome of this experiment suggests some possibility of aliasing at lines in the unusual situation that the periphery is refracted correctly, but is still consistent with our inability to see aliasing artifacts in the periphery under normal viewing conditions.

METHODS

All stimuli were generated on a PIXAR II computer controlled by a Sun 3/110, and presented on a 19 inch Sony Trinitron screen. The output intensity of the screen was linearized with a look-up table. The mean luminance of the screen was 24.5 cd/m², except during the line experiment, when it was 10.0 cd/m². Trials were run with natural pupils and the room lights on, producing pupil sizes of about 5 mm for observer DRW and 4 mm for observer SJG. Both observers were myopes with normal visual acuity when corrected. SJG wore glasses while observing; DRW did not, as the experimental set-up provided any spherical correction needed.

The observer sat 4 m from the screen. The stimulus field subtended about 3.5 deg. (This varied; see below.) The screen was viewed through two positive lenses (focal length = 254 mm), as shown in Fig. 2, which allowed the observer to focus the stimulus on the retina. Lens L₂ formed a real image of the screen, I, that the observer viewed through lens L₁, which was one focal length from the pupil plane. At the beginning of each block of trials, the observer focused the image of the screen by adjusting the axial position of L₂, resulting in only minor changes in image magnification. These changes were taken into account in the calculation of spatial frequency. We found that the continuous control of refractive state provided by these lenses made aliasing effects with gratings (see below) much easier to see. When the stimuli displayed on the screen were imaged on the eccentric retina, observers foveally fixated a high contrast grating, which was intended to provide a strong stimulus for accommodation. This fixation target was not viewed through the lens pair so that the stimulus could be corrected for off-axis refractive errors (Ferey, Rand & Hardy, 1931; Navarro, Artal & Williams, 1993), which were found in both our observers. To make accommodation as stable as possible, the fixation grating was positioned at the observer's resting focus. This was determined by having the observer adjust the position of the grating until it appeared sharp immediately after opening the eyes after a short rest. A distance of 65 cm was used for both observers.

We used three kinds of stimuli in these experiments: gratings, edges, and lines.

Gratings

A prerequisite for determining whether aliasing can be seen with edges is to establish that our observers can detect aliasing with gratings under our viewing conditions. Observers viewed 100% contrast, sinusoidal gratings presented for 500 msec on a CRT display. They made two settings by adjusting spatial frequency: the first corresponded to the highest frequency at which the
horizontal orientation of the gratings was just discernible; the second corresponded to the highest frequency at which the stimulus presentation could be detected. Points shown are the mean of four settings. These determinations were made at 0, 10, 20, and 40 deg along the horizontal meridian of the temporal retina of the right eye in each observer. Horizontal gratings were used to minimize the effects of lateral chromatic aberration.

**Low-pass filtered edges**

To find out which spatial frequency components of an edge were visible, we created a series of horizontal edges that were filtered with rectangular filters that abruptly truncated the spectrum at the cutoff frequency. This filter has the desired property that there are no spatial frequency components at or above the cutoff and all the components below the cutoff remain in their usual proportions. The filter produces ringing in the stimulus, which can be seen in Fig. 1(D, F), and in the luminance profile in Fig. 3(A). The edges were actually half of one cycle of a square wave with a fundamental equal to half a screen height. The low-pass filtering was done by constructing the square wave with only the components less than (and not including) the cutoff frequency. The unfiltered edge had 79% contrast; this allowed for the fact that a rectangularly filtered edge has a higher peak-to-peak amplitude than an unfiltered edge (the fundamental has \( \frac{1}{2} \) times the contrast of the full square wave), so a 100% contrast edge could not be used. The peak-to-peak contrasts in the filtered edges were all therefore somewhere between 79 and 100% and increased as the cutoff got lower. The highest frequency in the unfiltered square wave was roughly 64 c/deg (“roughly”, because of the variation in magnification for different settings of the far lens), and this component had a contrast of 1/511.

**High-pass filtered edges**

We also created a series of high-pass filtered edges to see if the highest cutoff that still allowed their detection was the same as the highest cutoff that allowed discrimination between the low-pass edges and the unfiltered edges. The high-pass filtered edges were produced by summing the sinusoidal components of a half-cycle-per-screen square wave from the cutoff to about 64 c/deg. The luminance profile of one such stimulus is shown in Fig. 3(B).

**Low-pass filtered lines**

We also tested for aliasing at lines, since they have a sharp change in luminance but have a flat spectrum rather than one that falls off with spatial frequency. Filtered lines were produced by adding the appropriate number of equal-amplitude cosine components. This produced a series of sinc functions with decreasing main lobe amplitude and increasing main lobe width with decreasing filter cutoff. The filtered lines had progressively less contrast with decreasing filter cutoff. The same cutoff used in obtaining the profiles in Fig. 3(A, B) was used to give the profile of a low-pass filtered line in Fig. 3(C).

The unfiltered line was the sum of the first 256 components of a comb function with a fundamental equal to one screen height, once again giving a highest frequency of about 64 c/deg. The unfiltered line had a peak-to-peak contrast of 100% and a contrast of 70% between the maximum and the mean background value.

**Procedure**

In each block of trials, edges generated using different cutoffs were randomly interspersed throughout the block. A two-interval forced-choice procedure was used, with 500 msec stimulus durations cued with beeps, 1 sec interstimulus intervals, and auditory trial-by-trial feedback. On each trial the observer indicated which trial contained the filtered edge or line. For each of 0, 10, 20, and 40 deg eccentricity, a Weibull function was fitted to the psychometric function (percent correct vs filter cutoff spatial frequency) using the Levenberg–Marquardt method (Press, Flannery, Tenkolsky & Vetterling, 1986, pp. 523–528), and a 75% threshold obtained from that curve. The Levenberg–Marquardt method weights the
results for each cutoff according to the number of trials that contributed to the percent correct obtained for that cutoff. In our experiment, the number of trials for each cutoff varied from 10 to 100, and was never fewer than 50 for the cutoffs in the region of the 75% threshold.

RESULTS

Gratings

The solid lines in Fig. 4(A, B) show the results when 100% contrast grating stimuli were presented to observers SJG and DRW respectively. Solid circles show the highest frequency at which the grating orientation could be discerned; solid triangles show the highest frequency at which the stimulus presentation could be detected by any means. In all the figures following, the SE bars lie within the symbols unless shown otherwise. The shaded area marks the range of spatial frequencies over which aliasing occurs for each observer. In this range, both observers reported the grainy, shimmery appearance typical of extrafoveal aliasing. These results establish that extrafoveal aliasing can be seen by our observers under these experimental conditions.

The open circles show Nyquist frequencies derived from anatomical estimates of the density of cone mosaic (Curcio, Sloan, Kalina & Hendrickson, 1990) at the same eccentricities. The conversions from millimeters on the retina to degrees of eccentricity were taken from Drasdo and Fowler (1974). The open diamonds and triangles show two estimates of ganglion cell Nyquist frequency, also based on anatomical data (Curcio & Allen, 1990). Calculating the ganglion cell Nyquist frequency is complicated by the heterogeneity of the ganglion cell population. Because we are interested in whether this population or some subset of it could produce aliasing in edges, we evaluated this possibility using the smallest subset of the population that might reasonably act as an independent sampling array underlying the resolution of high spatial frequencies. We have taken the total ganglion cell population and multiplied it by 0.8 to get the number of P-cells (Wasse, Grunert, Rohrenbeck & Boycott, 1989). The open diamonds show the Nyquist frequency calculated using the full P-cell population. The open triangles show the Nyquist frequencies calculated using only half the P-cell density, on the assumption that the on-center and off-center cells act as independent mosaics.

We have noticed that estimates of observers' spatial resolution made in this laboratory are consistently higher than those made in other laboratories (Frisen & Frisen, 1976; Thibos et al., 1987; Anderson, Mullen & Hess, 1991). We do not yet know if this is due to experimental or individual differences. Recent measurements of the optical quality of the eye (Artal et al., 1992) show that off-axis astigmatism is quite severe, so that correct refraction at each eccentricity provides a significant advantage, but even other studies that use interference fringes do not give such high resolutions as these. Previous studies have shown resolution to be predictable from ganglion cell densities in the monkey (Merigan & Katz, 1990) and the human (Frisen & Frisen, 1976). Figure 4 shows that the resolution thresholds of our observers clearly exceed the full ganglion cell Nyquist frequency at some eccentricities. This may be a case of supra-Nyquist resolution (Williams & Coletta, 1987), or it may be an indication that the anatomical estimates of ganglion cell densities do not match those of our observers.

Edges

The two solid lines in Fig. 5 show the cutoff frequency for the filtered edge that allowed 75% probability of discrimination from an unfiltered edge for each observer at four eccentricities. Since this spatial frequency is the highest frequency the observer can see in an edge we call it “edge resolution”. Neither observer reported any subjective evidence of aliasing in the edge discrimination task. At each eccentricity, the discrimination between filtered and unfiltered edges was based on the visibility of ringing in the filtered stimuli. The edge in the unfiltered stimulus never appeared ragged or distorted, as one might expect if it were producing aliasing. We also noted that when a filtered edge was indistinguishable from the unfiltered edge out in the periphery, it was usually because they both looked like normal edges, not

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**FIGURE 4.** Solid lines show resolution (orientation discrimination) and detection thresholds for two observers presented with square wave gratings. The shaded region between these two curves indicates the range of spatial frequencies that are presumed to be detected in aliased form. Nyquist frequencies based on anatomical estimates of the cone, full P-cell, and on-center P-cell mosaics are shown for comparison.
because both looked blurry, a point to which we will return later.

The open circles in Fig. 5 show the anatomical estimates of cone Nyquist frequency from Fig. 4. The solid squares show psychophysical estimates of observer DRW's cone Nyquist limits obtained in an earlier study using the orientation reversal effect (Coletta & Williams, 1987). The latter provides verification that the anatomical cone Nyquist measurements, though slightly higher, are roughly appropriate for this observer. The highest frequencies that can be seen in an edge by these observers fall well below the cone Nyquist at all eccentricities.

Figure 5 also shows the anatomical estimates of ganglion cell Nyquist frequencies from Fig. 4. It can be seen here that the assumption of independent on and off P-cell arrays is a conservative one with respect to the edge resolution results. The edge resolution curves never exceed the ganglion Nyquist frequency even if only half the P-cells are taken to be the appropriate substrate. If all P-cells are giving independent information about spatial position, then edge resolution should be compared with the upper of these two curves and is clearly always lower than the ganglion cell Nyquist frequency.

These data show that spatial frequencies in an edge that exceed the Nyquist frequency for either the cone mosaic or half the P-cell population are invisible at all the eccentricities we tested. There are at least two possible reasons why these components are invisible: either they do not have enough contrast on their own to be detected under normal viewing conditions, or they are being masked by the higher contrast low frequencies present in the edge. To determine the contribution of masking, we measured the detectability of the frequency components above the filter cutoff when presented without the frequency components below the cutoff. The observer discriminated the high frequency portion of the edge from a uniform field of the same mean luminance in a two-interval forced-choice procedure. Figure 6 shows the edge resolution data from the previous experiment (solid circles) along with the 75% thresholds from the condition where the low frequencies are absent (open circles). It can be seen that for observer SJG there is little, if any, effect of masking by the low frequencies. The same experiment run on observer DRW at 10 deg eccentricity showed an effect of about the same size. It appears that the main reason the high frequencies in an edge can not be seen is their low contrast. This result is similar to Campbell and Robson's (1968) finding that gratings with sharp edges (including square waves) can be distinguished from sine waves of the same fundamental frequency only when the first higher harmonic of the grating exceeds its detection threshold.

Lines

The 75% thresholds for the cutoff allowing each observer to discriminate a filtered line from an unfiltered line are shown in Fig. 7, along with the Nyquist frequencies from Fig. 4. These cutoff frequencies are higher than the edge resolution values for these two observers, but it is not clear that they are evidence of aliasing by the P-cell mosaic, because they are close to the Nyquist frequency. At 40 deg the thresholds for both observers exceed our best estimate of the ganglion cell Nyquist frequency...
frequency, but the SEs on these thresholds are large, as shown. The thresholds fall well below the cone Nyquist frequencies, so it appears that there was no aliasing of the line stimulus by the cone mosaic.

The observers were somewhat uncertain about whether the unfiltered line had the appearance of being aliased. Observer DRW reported that the unfiltered line looked rather broken up when viewed at 10 deg, and that this was a reliable cue for making the discrimination. This appearance might be expected if some mosaic were undersampling the line—it may appear to have gaps in it if no sample is taken for a significant distance along its length. Observer SJG also saw lines having this appearance, but tended to rely on the width and brightness of the line as a discrimination cue. This broken-up appearance may have been aliasing, but the effect was too subtle for us to be certain. Once again filtered stimuli presented in the periphery often had the appearance of being sharp, as they did when edge stimuli were used.

DISCUSSION

Neither of our observers could discriminate between filtered and unfiltered edges that differed only in their frequency spectra above the Nyquist frequency for half the P-cell population at each eccentricity. This is despite the fact that the rectangular frequency filter we used produced a strong ringing pattern in the filtered image which could assist as a discrimination cue. None of the cutoffs we used produced the artifacts we have come to associate with aliasing. We interpret this result to mean that even the coarsest sampling array in the retina that could plausibly be mediating the perception of high spatial frequencies is incapable of producing visible aliasing at each eccentricity.

An assumption made in reaching this conclusion is that only supra-Nyquist frequency components can produce aliasing. In principle, this is not necessarily true; analysis of the spectra of cone mosaics (Yellott, 1982) indicates that aliasing can be expected to begin below the nominal Nyquist frequency when sampling with irregular arrays. An example of aliasing of sub-Nyquist frequencies can be seen in Fig. 1(G), although some of this distortion is due to the reconstruction algorithm. In practice, however, it is clear that cone aliasing with grating stimuli becomes visible only when gratings are of high contrast and are close to or above the nominal Nyquist frequency (Tiana, Williams, Coletta & Haake, 1991). In our filtered edge stimuli, the discrimination thresholds were probably safely below the frequencies that might suffer aliasing, and the amplitude of the components that were being removed were low. Furthermore, the subjective reports of both observers argue against the notion that cone or ganglion cell arrays can produce edge aliasing. Observers never reported that unfiltered edges had the ragged appearance expected if aliasing were introducing distortion. The situation with line stimuli was less clear on this point, and there was some subjective evidence for aliasing.

If aliasing by a cone submosaic had been present in either case (Williams & Collier, 1983; Williams, 1990; Williams et al., 1991), one might have expected chromatic distortion at the edge, which neither observer reported.

The failure to observe aliasing in the laboratory with high contrast edges presented in isolation and in sharp focus on the retina demonstrates the importance of the properties of natural scenes as a protection from aliasing. This is indicated by our finding that the supra-Nyquist components of the edge presented alone were not even detectable with correct peripheral refraction. However, our experiment with line stimuli suggests that even when the spectrum is flat, aliasing is not necessarily detectable, possibly because aliasing is hard to see except as a disturbance in an extended two-dimensional regular pattern, or as spurious hues produced by small light sources, as in the case of stars fluctuating in color (Holmgren, 1884). The kinds of stimuli that have been used in the laboratory to produce aliasing through the optics of the eye are high frequency periodic patterns, such as a square or sine wave gratings. Such gratings have higher contrast supra-Nyquist frequency components (as high as 100%) compared with those of edges, the spectra of which fall as the inverse of spatial frequency. However, even for grating stimuli, aliasing distortion is only a few times contrast threshold under the very best laboratory conditions. Refractive errors which undoubtedly are commonplace in natural viewing, particularly for objects in the peripheral retina, may be sufficient to obliterate extrafoveal aliasing even for gratings, outside the laboratory. Though we found that the grainy appearance of an aliased grating could be seen by adjusting the focusing lens in our system, it was typically obliterated when the grating was viewed without the focusing system.

Even when viewed foveally, it appears that the combination of high frequencies in an edge has such low contrast that nothing above about 25 c/deg can be detected. It is interesting that spatial frequencies above 25 c/deg are apparently of little importance in human vision despite the fact that grating acuity extends to more than twice this value. These results are consistent with the finding that a small difference in the blurri ness of two edges is more easy to detect if both edges are a bit blurrier to begin with, rather than if one is blurred and one is sharp (Hamerly & Dvorak, 1981; Watt & Morgan, 1983). This can be explained if observers use relatively low frequency information in edges to discriminate differences in the amount of blur (Hess, Pointer & Watt, 1989).

Because edges generally appear sharp and undistorted in the periphery despite substantial blurring by the optics and spatial sampling, it is tempting to think of the visual system as having some mechanism that supplies a template for a crisp edge whenever the retinal information is consistent with such an edge. For example, once the evidence for the existence of an edge is sufficiently strong, the visual system could represent the edge as a sharp one, ignoring the discrepancies from this
interpretation as noise. Such a scheme would cause observers to fail to discriminate filtered and unfiltered edges as we observed. However, though our results do not rule out this kind of a mechanism, they do show that such a mechanism is not needed to clean up information from the retina that is distorted by aliasing, since our observers cannot detect these potentially offensive frequency components of edges even when they are presented in isolation (see Fig. 6). This shows that the supra-Nyquist components of edges are simply too weak to produce substantial distortion to begin with. Nonetheless, we noticed in the course of these experiments that even very blurry edges appeared sharp in the periphery, so perhaps the template scheme may help cope with the low spatial bandwidth of the visual system in the periphery, even if it is not necessary to explain the invisibility of extrafoveal aliasing.

Several factors have been proposed that might reduce the detectability of these high frequency components: blurring by the optics of the eye, retinal scatter, blurring by the cone aperture, disorder in the cone mosaic, blurring by eye tremor, and the low-pass filtering due to convergence of cones onto postreceptoral layers. New measurements of the off-axis optical quality of the eye (Artal et al., 1992) indicate that the optics provide protection against aliasing by the cone mosaic at the fovea and in the far periphery, but leave an annular region that is relatively unprotected. The P-cell mosaic appears to be left relatively exposed by the optics to aliasing everywhere beyond about 10 deg eccentricity. Nonetheless, considering those factors for which quantitative estimates are available, blurring by the anterior optics stands as the single most important factor in reducing extrafoveal aliasing for either the cone or ganglion cell mosaics. Blurring by the cone aperture (Chen, Makous & Williams, 1993), retinal scatter (MacLeod, Williams & Makous, 1992), eye movements (Packers & Williams, 1992), and irregularity probably play minor roles by comparison. Postreceptoral filtering could potentially play a large role particularly in the far periphery, but current models of aliasing are not yet sophisticated enough to provide quantitative predictions of this benefit.

CONCLUSION

We have given aliasing at edges its best chance to reveal itself by presenting observers with well focused high contrast edges, but we still do not see any aliasing at edges under these conditions. While previous studies have shown that there is insufficient protection from aliasing to prevent aliasing of grating stimuli, we have shown that aliasing is completely eliminated for more common stimuli like the edges used here. This suggests that the spatial frequency content of the environment is one important reason why we are not troubled by aliasing artifacts during normal peripheral viewing.

REFERENCES


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