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Sharpness Overconstancy in Peripheral Vision*

SUSAN J. GALVIN,†‡ ROBERT P. O'SHEA,† ABIGAIL M. SQUIRE,† DONOVAN G. GOVAN†

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Although much has been learned about the spatial sampling and filtering properties of peripheral vision, little attention has been paid to the remarkably clear appearance of the peripheral visual field. To study the apparent sharpness of stimuli presented in the periphery, we presented Gaussian blurred horizontal edges at 8.3, 16.6, 24, 32, and 40 deg eccentricity. Observers adjusted the sharpness of a similar edge, viewed foveally, to match the appearance of the peripheral stimulus. All observers matched blurred peripheral stimuli with sharper foveal stimuli. We have called this effect "sharpness overconstancy". For field sizes of 4 deg, there was greater overconstancy at larger eccentricities. Scaling the field size of the peripheral stimuli by a cortical magnification factor produced sharpness overconstancy which was independent of eccentricity. In both cases, there was a slight sharpness *under*constancy for peripherally presented edges blurred only slightly. We consider various explanations of peripheral sharpness overconstancy. © 1997 Elsevier Science Ltd.

Sharpness overconstancy   Peripheral vision   Edge blur

INTRODUCTION

The anatomy underlying human peripheral spatial vision compared with foveal vision is a sorry tale indeed: the optics accommodate primarily for the distance of fixated rather than peripheral objects (Fincham, 1951); even when accommodation is accurate, optical quality declines with eccentricity (Campbell & Green, 1965; Williams *et al.*, 1994); the density of retinal cells is much lower in the periphery (Curcio & Allen, 1990; Curcio *et al.*, 1990); and neural pooling is much greater in the periphery (Dacey & Petersen, 1992).

Our performance in psychophysical tasks reflects the optical and anatomical handicaps of peripheral vision. The minimum angle of resolution increases with increasing eccentricity (Weymouth, 1958), peripheral contrast sensitivity functions are depressed, with peaks shifted to lower spatial frequencies (Millidot, 1966; Pointer & Hess, 1989), and wavelength discrimination requires large stimulus fields in the periphery (Moreland, 1972). This convergence between anatomical and objective psychophysical data has encouraged us to think of peripheral spatial vision as poor.

Despite the measurable weaknesses of peripheral vision, we enjoy a quality of visual scene that is quite uniform from the point of fixation right out to the image of our spectacle frames. While we might be unable to read the text on the book page opposite the one we are reading, the page does not disappear into a haze. In particular, objects seen in the periphery do not take on blurred borders. The telephone does not look furry; the white page on the noticeboard does not look like a cloud.

Not only do we enjoy reasonable sharpness constancy in our peripheral vision, there are some circumstances in which we can observe some overconstancy, for blurred objects. Our attention was drawn to this fact in the course of an experiment when we noticed that when observers failed to distinguish between low-pass filtered and unfiltered edges in the periphery, it was because they both appeared sharp, not because they were both blurry (Galvin & Williams, 1992). To demonstrate this effect for yourself, choose a fixation point about 20–40 deg eccentric to Fig. 1, and evaluate the sharpness of the vertical edge in the centre of the square, then look directly at the edge.

We found that observers tend to judge this kind of edge to be sharper when viewed in the periphery. We call this effect *peripheral sharpness overconstancy*. We have quantified this observation by having observers report the apparent blur of edges presented in the periphery.

EXPERIMENT 1

Method

Four volunteers, the authors, aged between 21 and 40 yr, corrected to normal vision, participated. Stimuli were generated by a Macintosh II computer, and presented on two high-resolution Apple monochrome 12 inch monitors, with refresh rates of 67 Hz. Observers viewed low-pass Gaussian filtered horizontal edges, presented at 8.3, 16.6, 24, 32, and 40 deg eccentricity,

*The main results of these experiments were presented at the 1995 meeting for the Association for Research in Vision and Ophthalmology in Ft. Lauderdale, Florida (Galvin *et al.*, 1995).

†Department of Psychology, University of Otago, P.O. Box 56, Dunedin, New Zealand, e-mail: galvin@psy.otago.ac.nz.

‡To whom all correspondence should be addressed.

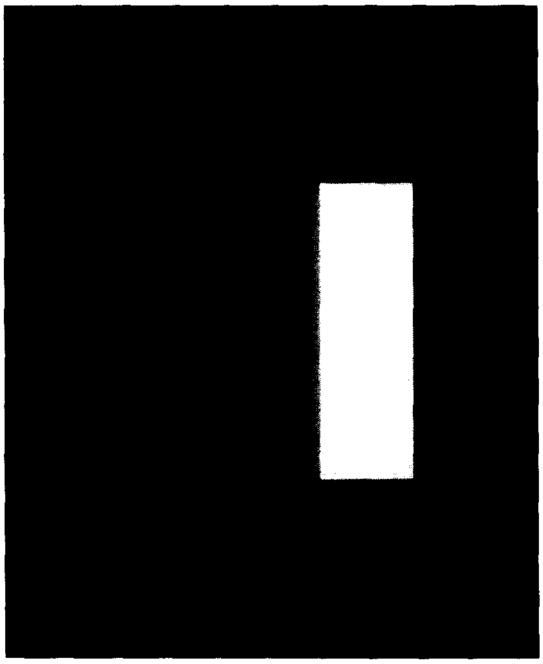

FIGURE 1. Hold the page about 30 cm from your face, fixate the outside edge of the opposite page, and judge the sharpness of the edge in the centre of the square field. Then fixate the edge. Which gives the sharper view?

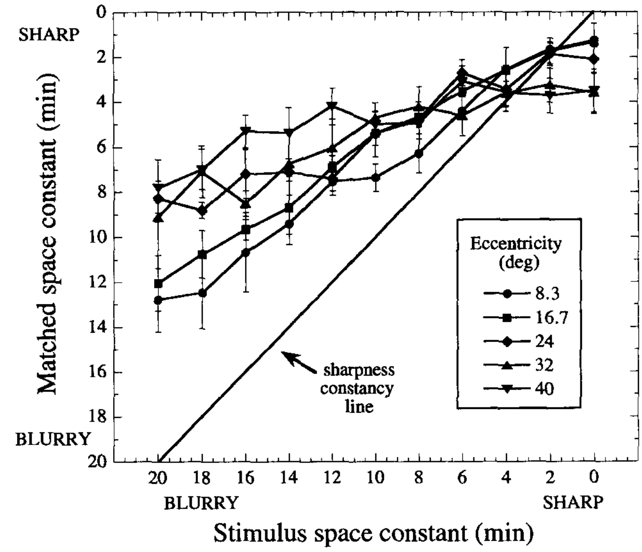

FIGURE 2. Mean response for four observers as a function of the stimulus space constant across the five eccentricities. Each point is the mean of four trials from each observer. Vertical bars show ± 1 SE of the four means. The diagonal line shows where the means would fall if the observers showed perfect sharpness constancy. The axes are plotted from largest to lowest space constant so that sharpness increases away from the origin, and points of overconstancy lie above the constancy line.

from a distance of 1.12 m. (At this distance, each pixel subtended 1 min of arc.) The edges were presented in 4×4 deg square fields centred in a 8×10.7 deg grey background of 55 cd/m^2, the mean luminance of the stimulus field. The contrast between the darkest and lightest regions of the stimulus was 0.95. The blurred edge profiles were cumulative Gaussian distributions spanning ± 3 standard deviations (SD). Eleven standard deviations, to which we refer as space constants, were used, varying from 0 (a sharp edge) to 20 min (a transition from light to dark spread over 2 deg) in steps of 2 min.

The vertical position of the peripheral edge was randomized over a ± 1 deg range to prevent the use of the size of the dark or light area in the stimulus field as a cue to the blur width.

Procedure

The temporal visual field of the left eye was tested; the right eye was patched. The peripheral monitor was set 4.8 deg higher than the central monitor so the peripheral stimulus would not fall on the blind spot. Observers had control of the space constant of a similar edge presented on a second monitor, viewed foveally. They took as long as they needed to adjust the sharpness of the central edge to match the appearance of the peripheral stimulus. At each eccentricity, each observer responded to each stimulus at least four times, with the order of presentation randomized.

Results

Figure 2 shows the space constants of the observers' foveal matches (y-axis) plotted against the actual space constants of the peripheral stimuli. Each point is the mean of the means for four observers, and the error bars show the standard error of those four means. The variability of individuals' data was similar to that of the pooled data.

All observers matched blurred peripheral stimuli with sharper foveal stimuli. This overconstancy was more marked at larger eccentricities. The results of all four subjects were quite similar, so the subjects' means were combined in a two-factor, within-subjects analysis of variance, which revealed an interaction between the stimulus space constant and eccentricity F (40,220) = 2.81, $P < 0.05$.

There was a slight sharpness *under*constancy for peripherally presented edges blurred only slightly.

Discussion

The data quantify the sharpness overconstancy phenomenon, and show more overconstancy at larger eccentricities. An interesting interpretation of these data would be that whatever mechanism produces sharpness overconstancy is more active further out in the periphery. The other possibility, consistent with the observers' reports, is that the stimuli were simply harder to see at the larger eccentricities.

We considered the idea that low visibility of peripheral stimuli had elicited guessing, making responses tend to the mean space constant, 10 min, and flattening the curve. We rejected this because we did not see more variability in the more eccentric conditions, and we found overconstancy for space constants less than 10 min.

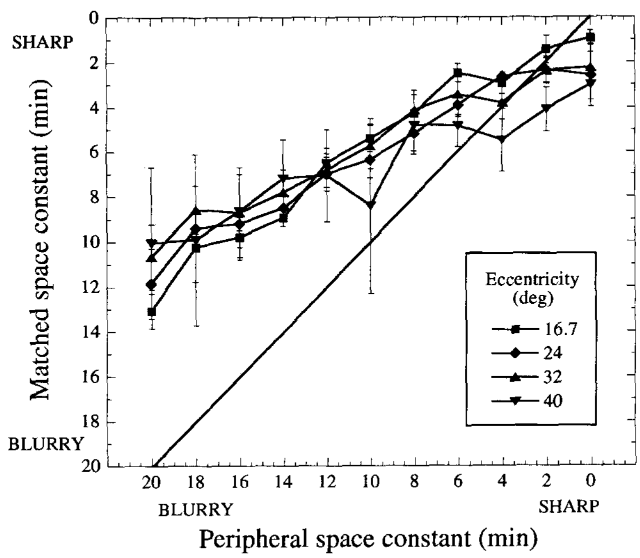

FIGURE 3. Response as a function of the stimulus space constant across the four larger eccentricities, with field sizes scaled by a cortical magnification factor.

EXPERIMENT 2

We were interested in whether the variation in the effect with eccentricity was due to the visibility of the peripheral stimuli. We scaled the field sizes of the peripheral stimuli by a cortical magnification factor, $M = 1 + 0.00012E^3 + 0.29E$, where E is eccentricity in degrees (Rovamo & Virsu, 1979).

Method

Square fields with side-lengths of 3.8, 5.3, 6.9, and 8 deg were used at 16.6, 24, 32, and 40 deg eccentricity, respectively. The foveal stimulus was not shrunk down to the appropriate M-scaled size because the blur widths used in the peripheral stimuli would not fit on a field that small. The stimuli at 8 deg eccentricity were not tested for the same reason. The same blur extents used in Experiment 1 were used in this experiment.

Observers were instructed to continue to match the apparent extent of the blur in the peripheral field, and to avoid adjusting the central blur so that it occupied the same proportion of its field as the peripheral blur took up in its field. Four trials were run for each space constant at each eccentricity for three observers, AS, SG, and ROS.

Results

M-scaling the peripheral fields produced sharpness overconstancy which was independent of eccentricity, shown in Fig. 3. The interaction between stimulus space constant and eccentricity was not significant $F(30,132) = 1.04$. Underconstancy is still evident for the least blurred peripheral stimuli.

Discussion

The results show that an edge that is obviously blurry when you look directly at it can appear quite sharp when you look away from it. To reassure ourselves that the effect is general, we conducted a scaled-down version of Experiment 2 as a class experiment for a statistics class of 97 students. In this experiment, one monitor with a screen subtending 17.2 deg by 12.5 deg was used. The stimulus field was square with side-length 4.7 deg. On each trial, the observer fixated a peripheral target while the test stimulus was presented for 150 msec, waited 1 sec, then fixated the stimulus field and adjusted the blur of a second stimulus to match that of the blur he or she had just seen. Each observer made four such settings at one of four eccentricities (0, 13.7, 22.1 and 31.4 deg) and at one of four blur extents (0–100 min of arc). For each observer, the mean of the peripheral settings was subtracted from the mean of the central settings to remove bias in the way observers made settings from memory. A two-factor (blur extent and eccentricity) between-subjects ANOVA showed significant sharpness overconstancy for blurred stimuli and underconstancy for sharp stimuli.

The exception to the tendency for things to look sharper in the periphery is that sharp edges presented in the periphery look slightly blurry—there is a limit to how sharp a peripheral object may appear. This may reflect intrinsic blur in the visual system. Levi & Klein (1990) found this to correspond to a Gaussian standard deviation of about 2 min of arc at 10 deg eccentricity in their observers; our observers match a sharp edge viewed at 8.3 deg with a foveal edge blurred with a space constant of 2 min of arc, which is consistent with the intrinsic blur measure.

The sharpness overconstancy effect is reminiscent of Georgeson and Sullivan's (1975) contrast constancy results for foveal vision—they found that despite differences in contrast threshold, sinusoidal gratings of different spatial frequencies presented at the same suprathreshold contrast were judged to have the same contrast. Brady & Field (1995) have extended these measurements to band-pass patterns. Georgeson (1991) found contrast overconstancy for gratings presented in the periphery. Sharpness overconstancy might be attributed to contrast overconstancy if high frequency components in the blurred edge were being amplified beyond the contrast present in the external stimulus. However, the effect we have observed cannot be due to a hyperactive contrast constancy mechanism, because it occurs for edges that have been blurred using a rectangular low-pass filter (Galvin & Williams, 1992). In that study, all frequency components above some cutoff were completely removed, so the apparent sharpness of the edge could not have been due to contrast enhancement of high spatial frequencies.

A factor contributing to sharpness overconstancy may be that peripheral vision is unable to code the luminance differences near the margins of the blur extent. This loss of information creates the possibility of incorrect perceptions. An inability to distinguish these luminances does not imply that the blurred region should look narrower, however, as the percept of the marginal region could be captured by either the blur or the neighbouring uniform fields. Similarly, coarse peripheral spatial sampling contributes to the uncertainty about the luminance profile of an edge, but knowing this does not enable us to predict whether an undersampled edge will appear sharp or blurry. Sinusoidal interference fringes of spatial frequencies known to be higher than the Nyquist limit of retinal arrays are perceived to be lower than the Nyquist limit (Williams, 1985, 1992), so we would not predict a sharpening effect from previous research on spatial undersampling.

Another possibility is that the apparent sharpness is produced by lateral inhibition, which is often thought of as a contour-enhancing process. Although the application of a band-pass filter to a stimulus cannot add power to high spatial frequencies, the removal of low frequencies can increase the contrast in the region of the edge, giving the impression of a steeper luminance gradient across it. A blurred edge might be sharpened in the periphery but not the fovea if the gradient of the blur were too shallow to influence the response of the small foveal receptive fields, but steep enough to stimulate differently the centre and surround of larger peripheral receptive fields. It seems unlikely, however, that lateral inhibition accounts for our results. If lateral inhibition were the only factor responsible for the illusion of sharpness, we would predict that blurred edges would look different at different eccentricities, as the spatial scale of the mechanisms underlying lateral inhibition increases with eccentricity (Dacey & Petersen, 1992). Yet the results of Experiment 2 show that observers make the same matches at different eccentricities, once the field sizes have been adjusted to make visibility uniform, providing evidence against the notion that sharpness overconstancy arises solely from lateral inhibition.

The sharpness overconstancy we have measured may be related to the sharpening of drifting, blurred images. Studies of motion deblurring have established that moving *sharp* images do not appear as blurry as one might expect (Burr, 1980). More surprisingly, a sequence of *blurred* stills looks sharp (Ramachandran *et al.*, 1974), and the edges orthogonal to the direction of motion of drifting, blurred squares are sharpened (Prather & Ramachandran, 1991). Unlike motion deblurring, motion sharpening and peripheral sharpness overconstancy both produce an image quality superior to that of the stimulus itself.

It may be that a higher-level explanation for these phenomena is necessary. When a blurred edge is presented in the periphery, the resulting percept seems to be a compromise between the incoming information and the percept of a straight edge. It could be that when incoming information about an edge is poor, a template of an edge derived from previous foveal viewing is applied. In the case of reading, for example, the regions of text in the peripheral visual field could be partly a reconstruction: our memory of the crisp text, obtained during our last glance at it, and reinforced by the uncounted number of pages we have already seen, endures in our perception. Bex *et al.* (1995), who examined motion sharpening of blurred edges, also concluded that humans harbour a default assumption that drifting edges are sharp. We are currently testing this idea by measuring apparent sharpness following different kinds of recent visual experience.

The assumption that edges are sharp is a clever one if a principal goal of the visual system is object recognition. Casual inspection reveals that most of the blurred luminance profiles in normal visual scenes are produced by lighting gradients, not by changes in reflectance across the surface of an object. Using a sharp edge template to construct perceptions from poor peripheral visual information is a way to discount the illuminant.

Peripheral sharpness overconstancy and motion sharpening provide a perception of objects as they are expected to be when they are viewed centrally and stationary, providing object constancy as objects move through the visual field. One might ask why these two mechanisms should be overconstancies, and not just constancies, if the goal is to allow the observer to perceive objects veridically. A possible answer to this lies in the original conditions under which the phenomenon was observed, namely, when a sharp edge and a blurred edge were indistinguishable, they both looked sharp. Sharpness constancy for sharp edges requires overconstancy for blurred edges: in order for the sharp edges to look sharp, anything blurrier producing the same visual information after low-level processing must also be made to look sharp.

Recently, Hammett & Bex (1996) proposed that motion sharpening could be the result of some non-linear operation adding high frequencies to the stimulus. They measured the apparent sharpness of a drifting sinusoid, and found that the sharpening effect was decreased by adaptation to a counterphased pattern made up of just the harmonics of the test sinusoid. We intend to apply a similar test to the addition of high frequencies as an explanation of peripheral sharpness overconstancy.

Whether the mechanism for peripheral sharpness overconstancy is high-level or low-level, it adds to a growing list of observations of enhancement of peripheral features. Examples of such enhancement are the peripheral brightening effect (Troland, 1930; cited by Marks, 1966, 1967), in which a dim peripheral stimulus appears brighter than it really is, and the fine grain movement illusion (Thorson *et al.*, 1969), in which a small peripheral movement appears larger then it really is. It is intriguing to ponder whether evolution has selected for these effects, perhaps increasing the salience of peripheral objects for the purpose of drawing fixations to them. They could also simply be side-effects of other mechanisms, for example, overconstancy for blur resulting from the system's efforts to provide sharpness constancy for sharp edges.

Conclusion

We have presented evidence for a new phenomenon, peripheral sharpness overconstancy, which allows an observer to experience blurred edges as sharper than they really are. It is as yet unknown whether this striking effect is due to low-level mechanisms, such as the introduction of high frequency components by non-linear processing, or the result of applying the sensible assumption that edges in the visual world are occlusion borders, and therefore, sharp.

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