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Simultaneous Blur Contrast

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ABSTRACT

How well-focused an image appears can be strongly influenced by the surrounding context. A blurred surround can cause a central image to appear too sharp, while sharpened surrounds can induce blur. We examined some spatial properties and stimulus selectivities of this "simultaneous blur contrast." Observers adjusted the focus of a central test image by a 2AFC staircase procedure that varied the slope of the image amplitude spectrum. The tests were surrounded by 8 identical images with biased (blurred or sharpened) spectra, that were presented concurrently with the test for 0.5 sec on a uniform gray background. Contrast effects were comparable in magnitude for image sizes ranging from 1-deg to 4-deg in visual angle, but were stronger for tests that were viewed in the periphery rather than fixated directly. Consistent biases were found for different types of grayscale images, including natural images, filtered noise, and simple edges. However, effects were weaker when surrounds and tests were drawn from different images, or differed in contrast-polarity or color, and thus do not depend on blur or on average spatial-frequency content per se. These induction effects may in part reflect a manifestation of selective contrast gain control.

Keywords: blur, image quality, simultaneous contrast, center-surround interactions, spatial vision, natural images

1. INTRODUCTION

We have recently begun a series of studies to examine how the visual system adjusts to image blur[1]. Accommodation of the eye's optics to maintain the quality of the retinal image is the obvious and perhaps principal visual response to blur. However, these adjustments are inherently imperfect because of aberrations, refractive errors, and the limited depth of focus provided by a finite pupil aperture. Moreover, they cannot correct for images which themselves are physically blurred, because of the actual content of the scene or the viewing conditions (e.g. fog or haze). What can the rest of the visual system do? We began exploring this question by asking whether mechanisms of adaptation could alter the neural response to retinal image blur. In these experiments subjects first viewed for a few minutes an image that was physically blurred or sharpened, and then varied the amplitude spectrum of a test image until it appeared properly focused. The results revealed large and rapid adaptation effects to blur[1]. Exposure to a blurred image caused the original, focused test image to appear too sharp, so that the image subjects selected as best-focused was in fact physically blurred. Conversely, adaptation to a sharpened image caused the original test to appear too blurred, and thus shifted the subjective judgments of best focus toward images that were physically sharpened. These "successive blur contrast" after-effects probably reflect response changes at a cortical locus arising from general processes of contrast (pattern-selective) adaptation, which are known to regulate sensitivity to many aspects of the stimulus. In the specific case of blur, these sensitivity adjustments may play a fundamental role in shaping and calibrating the visual system for the spatial structure of the visual world, over both short (e.g. scene-dependent) and long (e.g. developmental) time scales.

In the course of making these measurements we observed a second surprising form of neural adjustment to blur. Simply placing sharpened or blurred images near a focused image could cause it to appear blurred or sharpened, respectively. These interactions represent a spatial analog of the successive effects of adaptation, and appeared to induce changes in perceived focus that were in many cases as salient and striking as those we had observed following adaptation. The purpose of the present study was to examine some of the basic properties and characteristics of this "simultaneous blur contrast."

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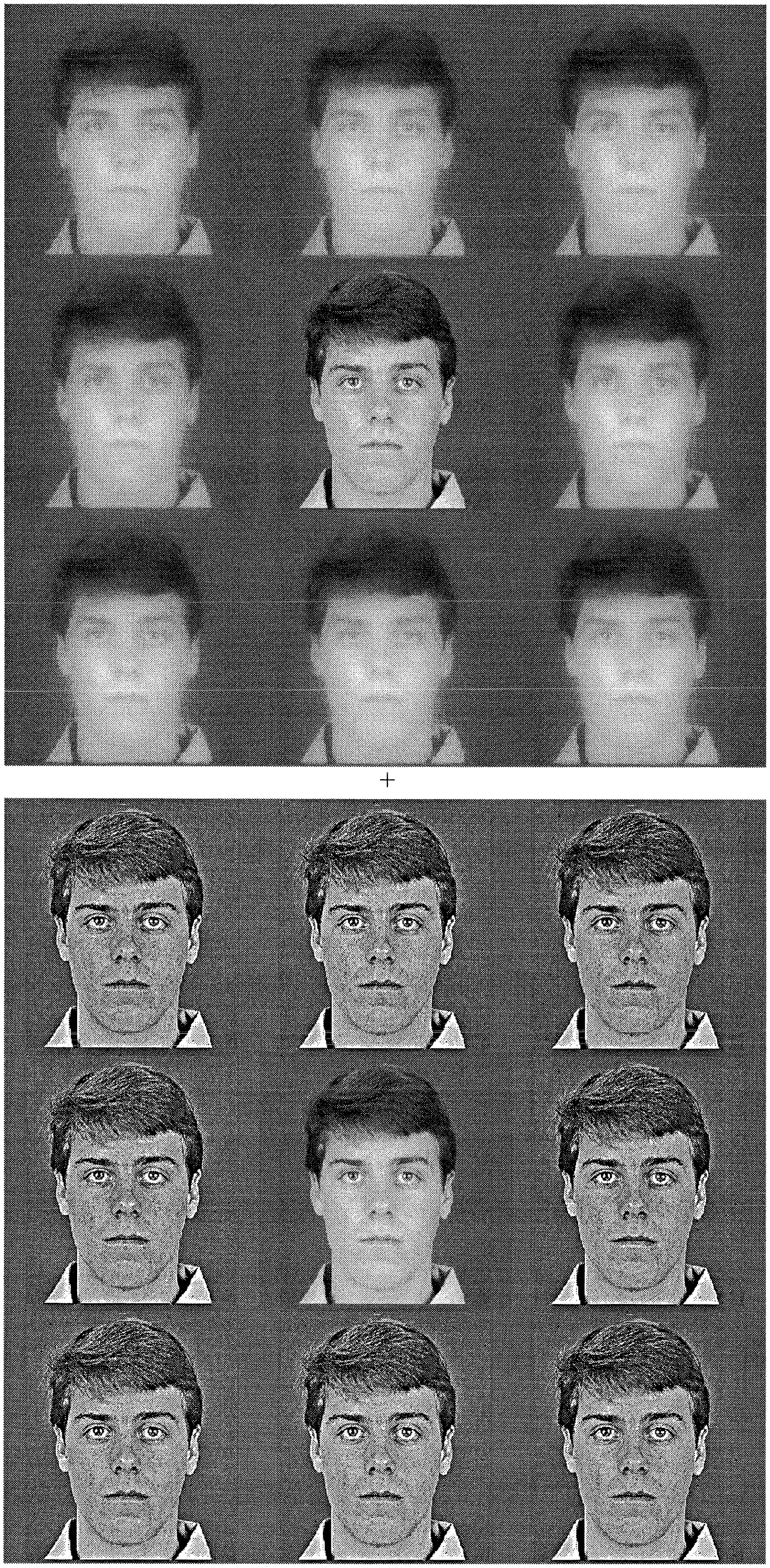


Figure 1. Stimulus configuration for measuring the contrast effects. The two arrays show the in-focus face image surround by blurred (b = -0.5) or sharpened (b = +0.5) versions of the face. Note during experiments only a single array was displayed.

2. METHODS

We used stimuli and procedures similar to those we employed to study the blur adaptation, in order to compare the properties and magnitude of the two types of adjustment. Most measurements were made for an image of a face (see Figure 1) or for a simple vertical edge. However, results were confirmed for a wide variety of images including those illustrated in Figure 1 of Webster et al.[1] The images had a resolution of 256 by 256 pixels and 256 luminance levels. The mean gray level for all images was fixed at a value of 100, corresponding to a mean luminance of approximately 10 cd/m^2. Stimuli were displayed on a standard color monitor, and were viewed binocularly in an otherwise dark room. For most experiments the viewing distance was 200 cm. At this distance individual images subtended 2-deg of visual angle, and had a maximum vertical or horizontal spatial frequency of 64 c/deg. They were shown centered in a 6 by 8 uniform gray surround of the same average luminance.

As in the adaptation experiments, we blurred or sharpened the images by filtering the amplitude spectrum of the original image by f^{β}, where f was the spatial frequency in cycles per image and β was an exponent controlling the slope of the filter on a log-amplitude vs. log-frequency plot. In the results below, both the stimuli and observers' settings are reported in terms of these β values. A negative value reduced the amplitude at higher frequencies and thus steepened the slope of the original spectrum, blurring the image. Positive values instead increased the amplitude at higher frequencies, producing shallower slopes and thus sharpening the image. By varying the slope over a wide range (-0.5 to +0.5) in small increments (0.01), we generated for each image a large array of test images that varied gradually from moderately blurred to moderately sharpened. Each image was adjusted after filtering to have the same mean gray level and the same rms contrast, removing these attributes as possible cues to the perceived focus.

In experiments we presented a central test image concurrently with eight adjacent surround images (see Figure 1). On each trial this 3 by 3 pattern was displayed on the screen for 0.5 sec. Blur in the surrounding images was fixed across trials, while observers adjusted the perceived blur of the central test image using a 2AFC staircase procedure. The magnitude of blur in the test image was initially set to a random value. Subjects used a pair of buttons to indicate whether this image appeared "too blurred" or "too sharp". If the subject responded "too blurred" then the next presented image was sharpened, or vice versa, so that over trials the staircase converged at the β value at which the two responses were equally likely. Settings continued for 9 reversals each in the responses of two randomly-interleaved staircases, with the focus point estimated from the mean of the final 6 reversal points of each staircase. A gap of 3 sec separated each trial. Conditions specific to individual experiments are described in the Results. Values reported are based on the average of 2 to 4 estimates per condition, with the adapting and test conditions counterbalanced across trials and daily sessions. Subjects included the authors and three additional observers who were tested on different subsets of experiments. All had normal or corrected-to-normal visual acuity.

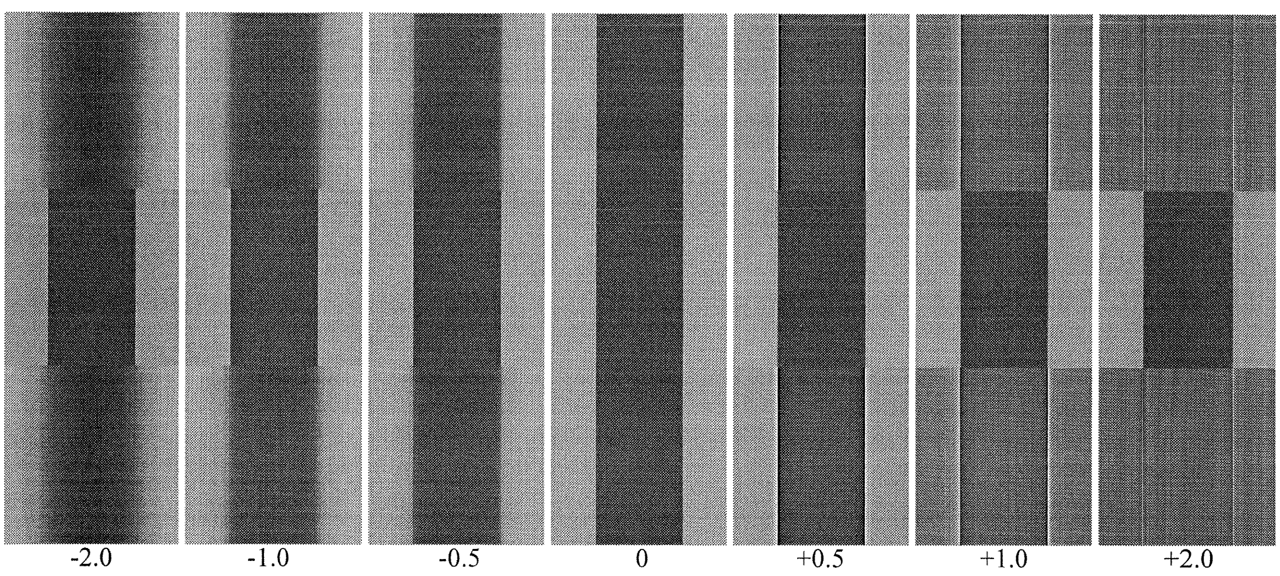


Figure 2. An illustration of the induction effects for simple edges. The center bars are identical square edges. However, bars abutting the blurred edges appear sharpened while bars abutting the sharpened surrounding bars appear blurred.

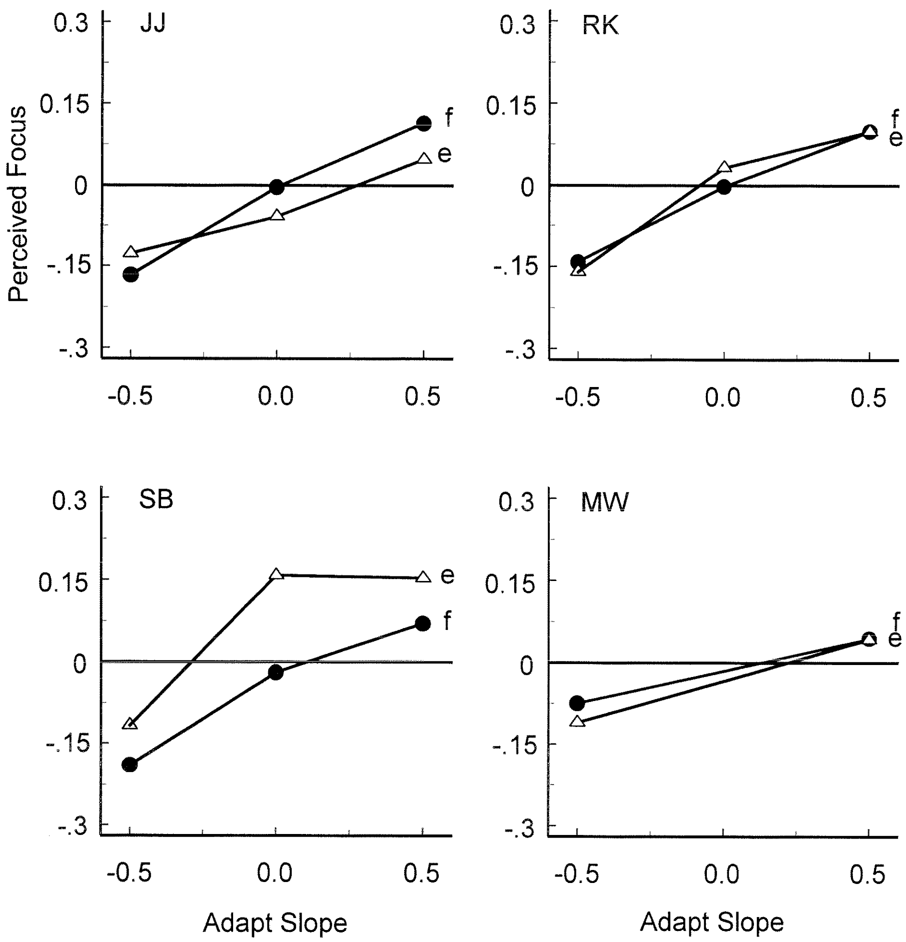


Figure 3. Shifts in perceived focus as a function of the filtering of the surround. The four panels plot the settings for four different observers, each tested for the face image (f) and the edge (e).

3. RESULTS

Figure 1 shows an example of the stimuli we used. The surround images in the right array are blurred by a slope of -0.5, while the surround in the left array is instead formed of images sharpened by filtering with a slope of +0.5. The two faces at the centers of the image arrays are physically the same and were taken from the original focused image. However, in our experiments they appeared different because of the different surround contexts (these differences can be seen in the original print but may be less visible in the reproduction.) The image in the blurred context appeared sharpened, while the image in the sharpened context appeared blurred. Consequently, the images that appear in focus to the observer are shifted toward the direction of the surrounding image slopes.

Figure 2 shows a second illustration of these interactions for simple vertical edges. The seven dark squares along the central strip are physically equal and are all formed from focused square edges, while the surrounding bars extending above and below vary from strongly blurred (-2.0) to strongly sharpened (+2.0). The squares within the blurred context appear markedly sharpened, so that the edges have a scalloped or Mach band-like appearance. Conversely, the squares aligned to the sharpened surrounding edges appear blurrier. (Notably, the effects in this demonstration appear much more striking for the blurry surround edges, and in fact are not clearly visible for the sharpest surrounds at the right of the figure. This difference could result from a variety of factors. However, in the present studies we explored only moderately filtered images of +0.5 or –0.5, and thus have not yet examined the basis for this observation.)

Figure 3 shows the results of actual measurements of these interactions, based on the stimulus arrangement illustrated in Figure 1. The four panels plot the settings made by four different observers. For each observer the slope that appeared in focus is shown either for the face image or the vertical bar, in the presence of face or bar images that were blurred or

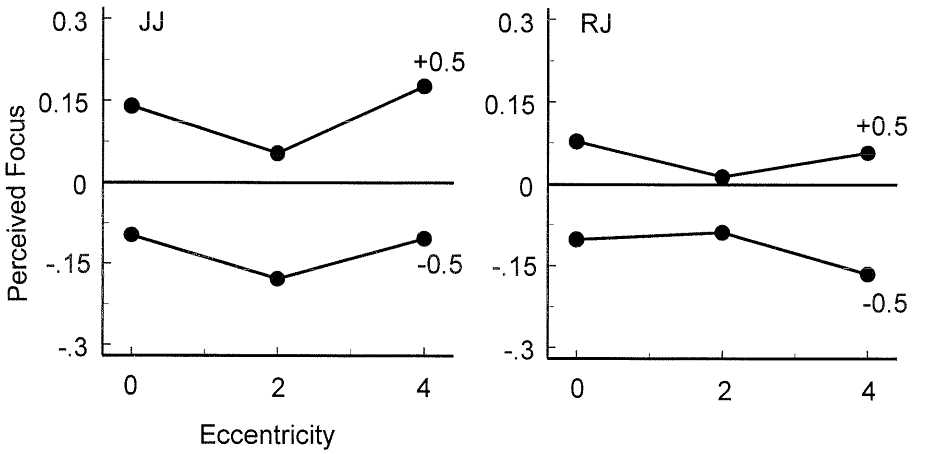


Figure 4. Changes in focus settings for the face image in blurred or sharpened surrounds, as a function of eccentricity. The two panels show results for two subjects.

sharpened by $\pm$0.5. Settings are also shown for either image measured on a uniform field surround (plotted at an x-axis value of 0). Notably, these settings were more difficult for the bar than for the face stimulus, a difference we also observed in our study of the adaptation effects[1]. Nevertheless, the basic interaction was strong and consistent across both the stimuli and the observers. Again, blurred surrounds caused the central test to appear too sharp or vice versa; and to null this induced sharpening, observers had to choose images that were physically blurred.

In the course of these experiments we quickly noticed that the blur contrast appeared at times much more salient when the images were viewed in the periphery rather than fixated directly. This may be visible in Figure 1 by fixating on a spot in between the two image arrays. We were therefore led to explore the dependence of the effect on eccentricity. Testing procedures were identical to those described previously, but now included three conditions in which observers directly viewed the 2-deg test or fixated at 2 or 4 deg to the left of the array center with the aid of small red fixation spots. (Note that the stimulus array was 6-deg across, so that for the peripheral viewing subjects fixated either the center of the left surround image or 1 deg from the left edge of this image.) Figure 4 again plots the settings for two observers for the face image, this time as a function of eccentricity. There is again a large and consistent induction effect, yet surprisingly it did not vary in a consistent way with retinal location. This may have resulted because observers did not have consistent criteria for judging the perceived focus of targets in the periphery. As a test for this, we ran further observers in a modified task in which two stimulus arrays were shown on each trial. During the first the surround elements were focused, while in the second (shown 500 ms later) they were filtered as in the original blurred or sharpened configuration. In this way subjects were only required to make a relative judgment about the perceived focus at the same relative locus, by responding whether the second image appeared more or less blurred than the reference image. As Figure 5 illustrates, this procedure did yield settings that suggested an increasing magnitude of induction for peripherally viewed targets.

Like many eccentricity effects, an increase in the induction in the periphery could reflect changes in the effective "receptive fields" underlying the center-surround interaction[2]. For example, if for foveal targets the interaction occurred only over a small spatial range, then the surrounding images may already have been too far removed from the central test to strongly influence it. To test this idea, we also measured the effects of image area on the blur contrast for directly fixated targets. This was done by varying the viewing distance of the observer, in order to maintain the resolution of the images on the display. Figure 6 shows an example of the results for one observer tested on the face image, and shows that there was not a clear change in the size of the effect over a four-fold change in image size, suggesting that the eccentricity effects probably cannot be equated simply by scaling image size. This is consistent with a recent report by Xing and Heeger[3] who examined center-surround effects on perceived contrast. Like the present results, they found that contrast induction is stronger in the periphery and that the effects do not scale with stimulus size, and argued from this that interactions in the fovea and periphery are qualitatively and functionally different.

With specific regard to spatial interactions in perceived blur, the effects of eccentricity are of further interest because blur itself is a feature that varies enormously with retinal location. That is, in normal viewing the foveal image is always embedded in a blurred context. An intriguing question is whether this blurred surround might actually sharpen the foveal image. In other words, is the neutral surround (i.e. the surround that does not affect the perceived focus of the test) an image

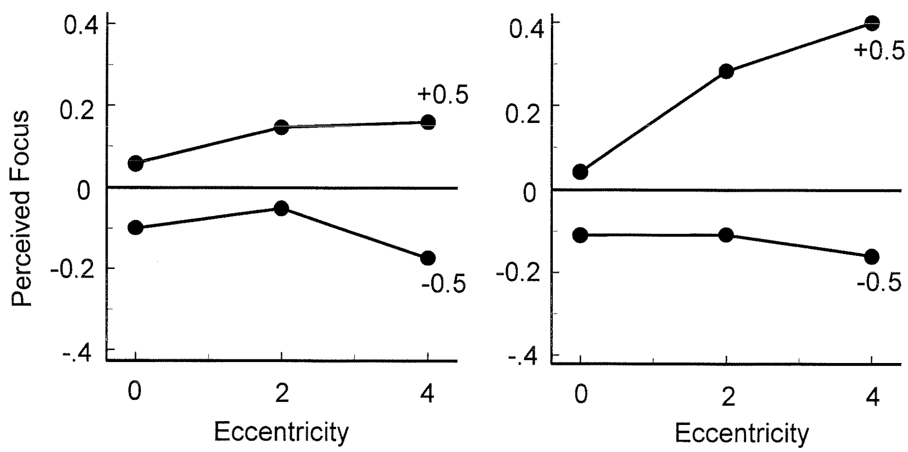


Figure 5. Remeasurements of eccentricity effects on the blur contrast, using a relative focus judgment. The two panels show settings for the face (left) or edge (right).

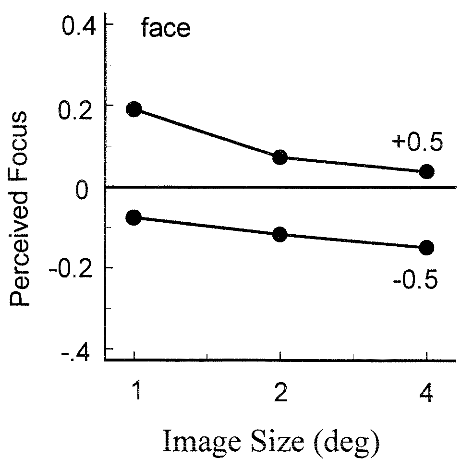


Figure 6. Effects of image size on the blur contrast, for directly fixated targets. Focus settings are shown as a function of the size of the central test image.

that is physically focused (and thus blurred on the retina) or an image that is physically sharpened (so that the retinal image has a "focused" amplitude spectrum). To test the latter case, we tried asking subjects to adjust the surround images until they looked as well focused as the centrally viewed image. However, under our conditions it proved impossible to dissociate the two measures. Subjects could perceive the blur in the image, but nevertheless chose images that were physically focused, presumably because they knew how much peripheral blur is expected for images optimally focused in the periphery. We therefore instead were able to test only the former case – of the effect of physically focused surrounds that are blurred by the peripheral visual system. These neutral surrounds had little effect on the perceived focus of the foveal targets. While not compelling, this result is at least suggestive of the possibility that the blur contrast effects are calibrated to compensate for the variations in spatial resolution across the visual field.

In the final set of experiments we examined how selective these interactions are for the properties of the center and surround stimuli. The adaptation after-effects we observed were strongest when the test and surround were drawn from the same image[1], and a similar result holds for the simultaneous interactions. For example, Figure 7 plots the change in perceived focus as the surround was varied from +0.5 to –0.5 for two images (the face image or an image of leaves), when either was surrounded by a variety of different filtered images (shown in Figure 1 of Webster et al.[1]). Biases were largest when the surround was a blurred or sharpened version of the same image, indicating that the induction does not depend on the blurriness or sharpness of the surround per se. More surprisingly, the induction was also strongly selective for the polarity of the image contrasts. For example, Figure 8 shows the change in perceived focus for the face or the vertical bar when surrounded by images of the same or opposite contrast. A strong contrast-dependent interaction is evident, particularly for the

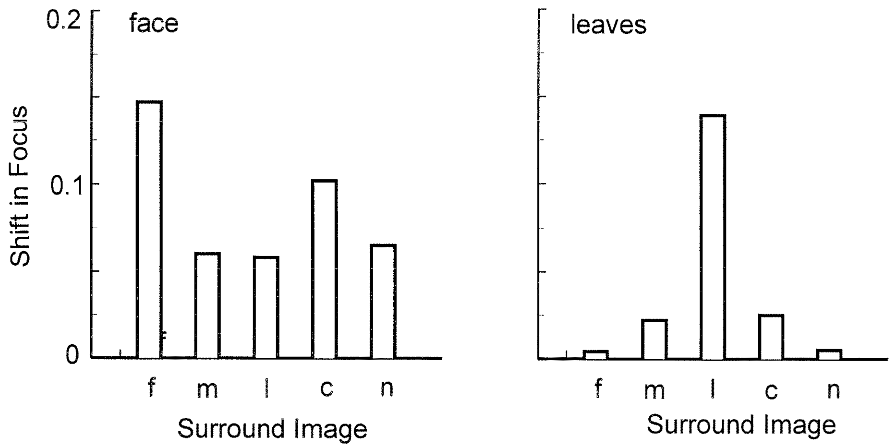


Figure 7. Selectivity of the blur contrast for different images. Plots show the magnitude of the biases (measured as the difference between the selected focus points for the +0.5 and –0,5 surrounds) when the face (left panel) or an image of leaves (right panel) was surrounded by the same or different image (from the set shown in Figure 1 of Webster et al.[1]). Images are indicated by f: face; l: leaves; m: meadow; c: checkerboard; n: noise.

bar stimuli, as visible in the illustration at the bottom of the figure. Note that this configuration is similar to the stimuli giving rise to grating induction, in which an illusory grating is generated in a field between two gratings. This could in principle affect the perceived focus if the induced grating added or subtracted from the response to the physical test. However, we observed little grating induction for our stimuli, and a "superposition" process of this sort could not plausibly underlie the blur effects for complex amplitude and phase spectra characteristic of the natural images. Note also that in the case of the bar stimuli, the change in contrast polarity could equally refer to a change in edge positions, and this misalignment might better describe the basis for the effect. More generally, it is possible that the effect is reduced by any manipulations that serve to differentiate the center and surround regions. Indeed, we also observed in informal measurements that the effect was diminished just by tinting the images so that the center and surround had different average chromaticities, even though the luminance contrasts in this case remained the same.

4. DISCUSSION

In summary, we have found that the perception of blur is a strongly relative judgment – relative to both the spatial context in which the images are judged, and the recent history of images to which the observer is adapted. Center-surround interactions of the kind we observed are a widespread phenomenon, modulating the perception of color, contrast, and form. Perhaps the most relevant to the effects we examined are the changes in perceived spatial contrast induced by contrast in surrounds[4-7], and changes in perceived frequency of tests induced by surrounding gratings[8]. As noted, our results for simple edges might also be related to a form of grating induction, though it less clear that this could underlie the blur induction for complex patterns. Contrast induction effects tend to show rather broad selectivity, and become even less selective in the periphery[3]. However, if these interactions underlie the blur contrast, then in some sense they must be strongly selective, for the blur judgments themselves depend on comparisons of relative contrast across different spatial scales. This could arise if the center-surround interactions for contrast were relatively independent at different scales. However, it is unlikely that the blur effects depend on a simple process of this sort, for we have shown that the effects cannot be predicted simply from the amplitude spectrum and instead can be highly sensitive to both the spatial and contrast properties of the stimuli. Moreover, the very perception of blur cannot be predicted from the overall spectrum, for it depends on judging the amplitude of contrast at different scales independently of the amount of energy across scale[9].

One role of spatial interactions may be to normalize the visual response to contrast[10], and this provides a possible account of the perceived blur effects. If observers are normalizing to the background images, then they should appear less blurred, and this perceptual shift should cause an in-focus test to appear biased in the opposite direction. We argued in the context of the adaptation that normalizations of this sort may be important for compensating for the short and long term variations in the quality of the retinal image[1]. To explore these normalizations it is important to map the changes in perceived blur more completely. Our present method measures only a single point (the point of subjective best focus) and thus does not reveal how the perception of the surround or adapting stimuli are themselves changing (though subjectively it seemed evident that during viewing the adapting stimuli progressively appear less filtered). We are currently exploring this question. Normalizing to the surround might serve to recalibrate the perception of blur, and in this sense represents a global or at least spatially extended adjustment. But a second possible function of spatial induction effects is to accentuate the perceptual differences

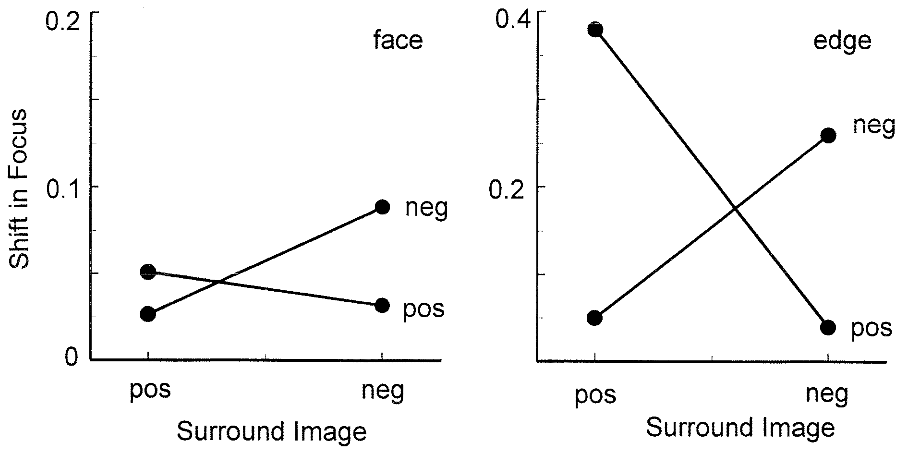
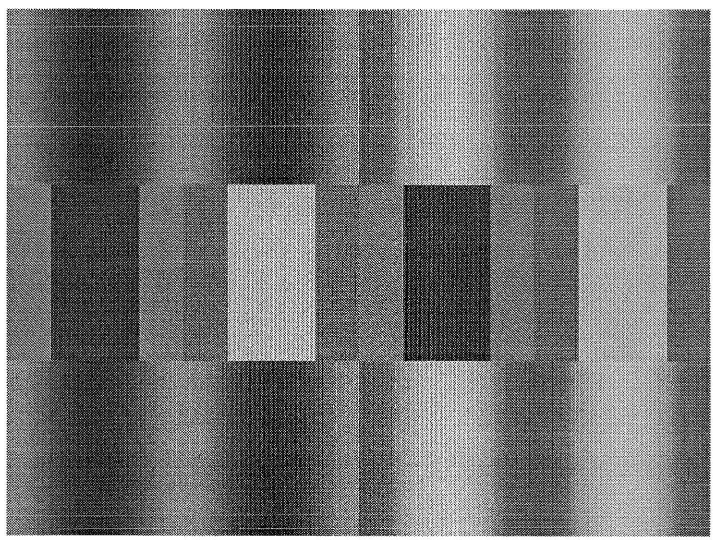


Figure 8. Selectivity of the blur contrast for the polarity of the image contrast. Values show the change in the focus settings (i.e. the difference in the settings for sharpened vs. blurred surrounds) when the face or the edge was shown surrounded filtered versions of the same image or the contrast-reversed image.

An illustration of the polarity selective effects for simple edges. The blurred surrounds sharpen only the same-polarity edges.



between different retinal regions. In this regard the interactions we have observed may reflect a specific example of a more general phenomenon of "simultaneous texture contrast," and we might expect to see comparable effects for different dimensions defining textures. It is not certain why highlighting perceptual differences might be advantageous for the specific dimension of blur, but the limited depth of focus of the eye suggests that for natural three-dimensional scenes there will often be local differences in image blur. The interactions we observed could serve to highlight these blur differences between objects at different distances, and perhaps through this accentuate the presence of the depth differences.

As we noted initially, we were led to these experiments by studies that first examined the effects of adapting to changes in blur over time. Spatial analogs of pattern-selective after-effects are common and have been reported for many basic stimulus attributes, including color, motion and form. For example, the center-surround effects on apparent contrast that we noted above appear similar to the changes in perceived contrast induced temporally by contrast adaptation[11]. Do these spatial and temporal experimental paradigms reflect distinct processes in the visual system, or do they merely reveal the same underlying sensitivity adjustments in a different context? The answer to this question remains uncertain, though there are several indications that qualitatively distinct processes are involved. The first concerns the spatial and temporal properties of the effects. In principle, the "simultaneous" spatial influences on blur could reflect very rapid adaptation that is not strongly selective for retinal location. However, we found that the contrast effects persisted over large retinal areas (e.g. up to 4-deg test images), while contrast adaptation effects must be relatively well localized in space because they are routinely measured by asymmetric matching procedures, in which different retinal regions are under different adaptation states. Moreover, we have observed the center-surround interactions even when the surround alternates between blurred and sharpened images at rapid rates so that there is little time for adaptation to build up. A second source of evidence supporting a dissociation is with regard to the nature of the sensitivity changes. Our present results do not reveal whether sensitivity is affected in different ways by the spatial and temporal context. However, Klein, Stromeyer, and Ganz[8] reported a difference for shifts in apparent spatial frequency resulting from adaptation to gratings versus induction from surround gratings. Specifically, they found that both adaptation and induction could alter the perceived frequency of a test grating, but only adaptation altered the contrast threshold for detecting the grating, and from this argued that two different processes were involved. A third potential source of evidence could come from looking at how the effects vary across retinal location. We showed that the magnitude of the spatial blur induction increases as stimuli are moved into the periphery. Xing and Heeger[3] found that spatial interactions in perceived contrast also increase with eccentricity and that they become much less selective for the properties of the test and surround stimuli. It would be of interest to test whether the adaptation effects vary with eccentricity in similar ways. Finally, one could look for a possible distinction by asking whether there are any temporal adaptation effects that do *not* have a measureable spatial analog. One case we have discovered is with regard to adaptation effects on face perception. Viewing a distorted face induces a large figural after-effect in the appearance of other faces[12, 13] (e.g. a face with an expanded configuration makes the original face look contracted). However, we could not induce a comparable shift by surrounding a face with distorted images. In part this may be because sensitivity to small configural differences falls rapidly with eccentricity, yet the face adaptation effects are comparable across very large changes in image size (so that the configuration extends well into the periphery)[14]. In any case, these observations collectively suggest that the spatial and temporal adjustments in the visual system do depend on separable mechanisms and may subserve different functions in perception.

5. ACKNOWLEDGMENTS

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