Adaptation to Blur

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ABSTRACT

Blur is an intrinsic property of the retinal image that can vary substantially in natural viewing (e.g. because of optical errors). We examined how processes of contrast adaptation might adjust the visual system to regulate the perception of blur. Observers viewed a blurred or sharpened image for 2-5 minutes, and then judged the apparent focus of a series of 0.5-sec test images interleaved with 6-sec of readaptation. A 2AFC staircase procedure was used to vary the amplitude spectrum of successive tests to find the image that appeared in focus. Adapting to a blurred image causes a physically focused image to appear too sharp (so that the image that appears in focus is physically blurred). Opposite after-effects occur for sharpened adapting images. Pronounced biases were observed over a wide range of magnitudes of adapting blur, and were similar for different types of blur. After-effects were also similar for different classes of images (e.g. natural scenes, filtered noise, or simple edges) but were generally weaker when the adapting and test stimuli were different images, showing that the adaptation is not adjusting simply to blur per se. These adaptive adjustments may strongly influence the perception of blur in normal vision and how it changes with refractive errors.

Keywords: blur, contrast adaptation, spatial vision, natural images

1. INTRODUCTION

Blur is a fundamental dimension of image quality. The optical image formed on the retina is inherently blurred, and in the course of normal viewing the magnitude of the blur changes substantially owing to changes in viewing conditions of both the physical scene (e.g. changes in the distance and relative depth of objects) and the observer (e.g. changes in accommodation or pupil diameter). Moreover, the degree of blur can differ widely across observers or in the same observer over time because of differences or changes in refractive errors. The prominence of such errors and the obvious advantages of correcting for them suggest that humans may be highly sensitive to changes in blur, and that judgments of blur are a routine and natural part of visual perception. In this study we examined to what extent these judgments are malleable, and specifically, to what extent they depend on the observer's state of spatial adaptation.

To a first approximation, variations in blur correspond to changes in the relative amplitude of structure at different spatial scales in the image[1]. For natural images, the amplitude spectrum of an in-focus image has a characteristic form, in which amplitude is roughly inversely proportional to spatial frequency (~1/f; or falls with slope $\alpha = -1$ on a log amplitude vs. log frequency scale; though the slopes of individual images varies substantially around this average)[2-8]. The spatial filtering characteristics of ganglion and LGN cells and of neurons in the striate cortex appear well matched to this property, compensating for the low-frequency bias in the physical stimulus so that the neural image is effectively whitened[4, 9, 10]. This match is also suggested by the perceived spatial structure of natural images. Stimuli with natural ($\sim f^{-1}$) amplitude spectra appear to have equal energy at all spatial scales, while an image with a spectrum that is physically flat (e.g. white noise) instead appears dominated by the high frequency structure[1]. Moreover, Tadmor and Tolhurst[11] and Field and Brady[1] showed that observers are good at adjusting the amplitude spectrum so that the image is in proper focus, and choose images that are close to the original spectrum. In their experiments observers altered the focus by varying the slope of the image spectrum. Increasing the slope (e.g. to α values more negative than the original) biases the spectrum toward lower frequencies and causes the image to appear too blurred, while reducing the slope boosts the relative amplitude of higher frequencies and causes the image to appear too sharp. (Note that observers were not simply setting the images to have a common amplitude spectrum, for as noted, individual images vary in their specific slope, and observers reliably chose the appropriate slopes for

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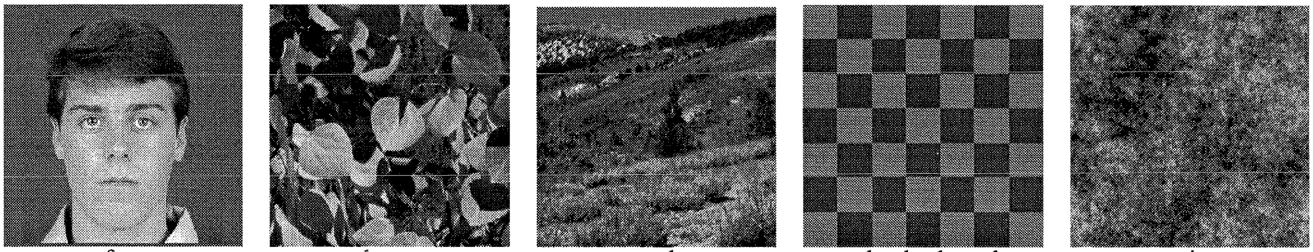


face leaves meadow checkerboard noise

Figure 1. Images used as stimuli to assess the blur adaptation effects, shown at their presumed "in focus" point. The face image was scanned from the stimulus set of Matsumoto and Ekman[12]. The leaves and meadow were taken from the natural image set used by Webster and Miyahara[8]. The noise image was generated by filtering white noise to a 1/f amplitude spectrum.

different images.) That observers could set the image spectrum correctly - and even for filtered noise patterns chose slopes close to the average for natural scenes - suggests that the visual system is well matched to or has good a priori knowledge about the spatial structure of images. But how can this knowledge accommodate to the large variations in blur that routinely arise both within and across individuals? We asked whether this match between spatial vision and the visual stimulus can in part be shaped by short-term adaptations in the neural response to the image structure.

The processes of contrast (pattern-selective) adaptation adjust sensitivity to many dimensions of the stimulus[13]. Among the most widely studied have been spatial contrast adaptation effects. Viewing a grating of a particular frequency and orientation produces a loss in sensitivity that is selective for the specific adapting grating[14-16], and biases the perceived frequency and orientation of subsequently-viewed test stimuli so that they appear less like the adapting stimulus (as seen in tilt[17] and spatial-frequency[18] after-effects). These after-effects are thought to reflect sensitivity changes at the level of the cortex[19-21], and show selectivities that are generally consistent with the spatial-frequency and orientation tuning observed in striate neurons[22, 23]. Webster and Miyahara[8, 24] examined whether the visual system might adapt selectively to the biased frequency spectrum of natural images, by measuring how exposure to natural images alters the sensitivity to different test frequencies. They found that after adapting to focused images, contrast thresholds for detecting low- to medium-frequency test gratings were selectively elevated. Moreover, adapting to images that were strongly sharpened or blurred (either physically or by introducing refractive errors), led to corresponding changes in the thresholds (so that sensitivity at lower frequencies was affected either less or more, respectively). These results thus suggest that adaptation does selectively adjust the visual system to changes in the degree of blur in the current retinal image(s). However, large changes in the adapting stimulus (e.g. slopes of –1 vs. –2) produced only weak changes in the shape of the contrast sensitivity function describing sensitivity to different frequencies. Thus, these studies did not reveal whether the visual system could be tuned for modest changes in blur. Further, measures of threshold sensitivity may poorly predict the nature of the adaptation effects for more natural judgments about more natural, suprathreshold stimuli. In the present study we chose to examine the adaptation effects within a more natural visual context, by directly asking how judgments of image blur are affected by adaptation to blur. To test this, we had subjects adjust the perceived focus of images after viewing and thus adapting to images that were physically blurred or sharpened. These measurements reveal surprisingly strong and selective after-effects in blur perception, and suggest that adaptation probably strongly influences judgments of image focus in everyday viewing.

2. METHODS

Adaptation effects were measured for a variety of different grayscale images. The images used are illustrated in Figure 1. These included images of natural objects (e.g. a face) or textures (e.g. foliage), structured edges (e.g. a checkerboard pattern), or unstructured noise filtered to a 1/f amplitude spectrum. The images had a resolution of 256 by 256 pixels and 256 luminance levels. All were adjusted to have a mean gray level of 100, equivalent to a mean luminance of approximately 10 cd/m^2. The stimuli were displayed on a standard color monitor in an otherwise dark room. Observers viewed the monitor binocularly from a distance of 100 cm. At this distance the images subtended 4-deg of visual angle, and had a maximum vertical or horizontal spatial frequency of 32 c/deg. They were shown centered in a 12 by 16 uniform gray surround of the same average luminance.

For each test image, we generated an array of stimuli by blurring or sharpening the original image over a range of magnitudes. The filtering was achieved by multiplying the original amplitude spectrum by f^{β}, where f was the spatial

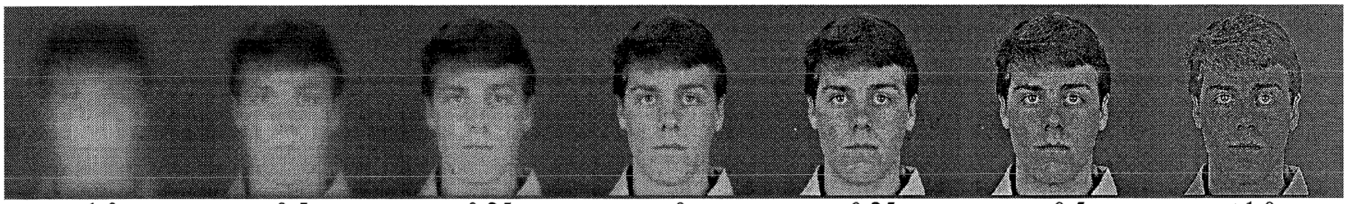


Figure 2. An example of the set of adapting stimuli, shown for the face image. Numbers below each image indicate the change in the slope of the original amplitude spectrum.

frequency in cycles per image and the exponent β controlled the magnitude of change. Negative values of β progressively reduced the amplitude of higher frequencies and thus blurred the image, while positive values increased amplitude with increasing frequency and thus sharpened the image. For most test stimuli β was varied from –0.5 to +0.5 in steps of 0.01, forming a series of 101 images that allowed us to adjust the magnitude of blur in finely graded increments. Once filtered, the image pixel values were rescaled to have the same mean luminance and rms contrast as the original image, so that the degree of blur was not correlated with image contrast. These procedures are similar to those used by Tadmor and Tolhurst[11] and Field and Brady[1]. Adapting images were drawn from images filtered in the same way over a range of –1.0 to +1.0. Figure 2 illustrates an example of the stimulus array created for the face image, and in particular shows the 6 different adapting levels we examined in the first experiment.

Perceived focus was measured using a 2AFC staircase procedure. Test stimuli were presented on the screen for 0.5 sec. The magnitude of blur in the image was initially chosen at random from the image array. The observer used a pair of buttons to indicate whether the 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. To examine the effects of adaptation, subjects first viewed a blurred or sharpened image for a period from 2 to 5 minutes. The test images were then displayed interleaved with 6-sec periods of readaptation for the duration of the staircase, with the test and adapt images separated by 0.25-sec gaps. For neutral adaptation, the same testing sequence was repeated with the adapting image replaced by a uniform field. 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.

3. RESULTS

Figure 3 illustrates the basic after-effects of adaptation to blur. The three panels show the results for three different observers. The four plots within each panel show the effects measured for a different adapting and test image (the three natural images and checkerboard shown in Figure 1). Results were qualitatively similar across the different subjects and for the different types of images examined. In each case, adaptation to a blurred image caused the original image to appear too sharp, and thus shifted the perceived focus toward blurrier test images. Conversely, adapting to the sharpened image caused the original to appear too blurred, and thus biased the settings toward sharper images. Note that the values plotted show the change in *physical* image blur required to null the change in *perceived* image blur, and thus are opposite in sign to the actual visual after-effect. In general these nulls came close to canceling the after-effect, so that the chosen images again appeared properly focused and similar to the original image viewed under neutral adaptation (though some residual differences in contrast and appearance remained). Note also that the null points indicate that the after-effects occurred over a wide range of magnitudes of adapting blur, and were perceptually pronounced. For example, the β values for the selected focus points shifted by up to ±0.3 for the strongly biased adapting images. As the ±0.25 images in Figure 2 illustrate, changes of this magnitude are highly salient when viewed under a constant state of adaptation.

In Figure 3, the adapting values of 0 corresponded to neutral adaptation to a uniform field, and not adaptation to the original focused image. These settings thus illustrate observers a priori expectations about image focus. As shown previously[1, 11], subjects were reasonably good at adjusting the images to their original spectrum, even though these spectra had different intrinsic slopes (see below). Notably, these judgments were easiest for the natural images tested, and harder for both the checkerboard and the filtered noise. In particular, for our conditions the filtered noise required substantial feedback in order to learn the desired 1/f setting, and was therefore only included in later experiments described below.

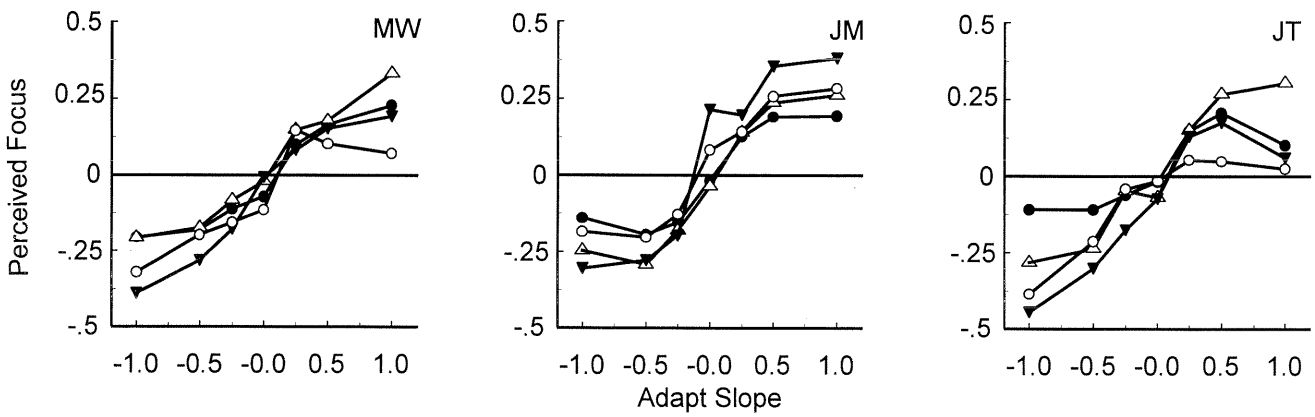
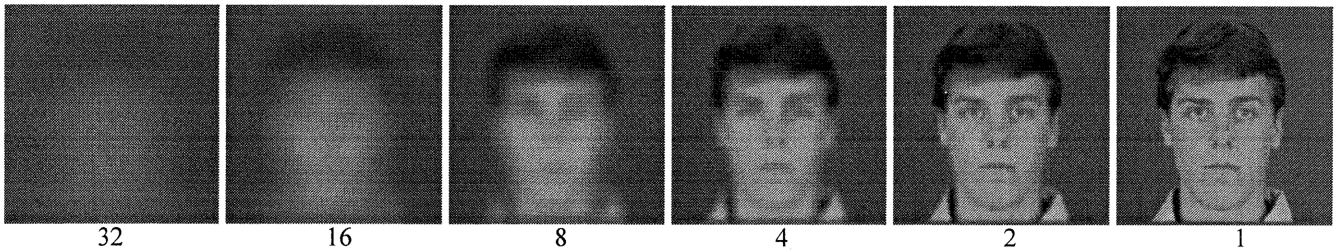


Figure 3. Perceived focus following adaptation to blurred or sharpened images. Values plot the image slopes that appeared best-focused as a function of the slope of the adapting image. The three panels are for three individual subjects. The curves within each panel show the settings for the face (filled circles), leaves (unfilled triangles), meadow (filled triangles) or checkerboard (unfilled circles), after adapting to filtered versions of the same image.

Biasing the spectral slope of images clearly appears to blur or sharpen the image, but differs from the filtering effects of optical defocus, especially since we renormalized image contrast after filtering. To approximate the effects of optical variations more closely, we also examined the adaptation effects for images filtered by simple Gaussian blur without correcting for changes in contrast. This also allowed us to examine the adaptation over a wider range of blur magnitudes. The stimulus arrays in this case were created by convolving the image with a Gaussian point spread function, with the standard deviation of the Gaussian varied in increments of 0.1 pixels. Figure 4 shows the resulting set of adapting stimuli for the face image, with standard deviations varying from 1 to 32 pixels. Figure 5 shows a plot of the null settings as a function of the adapting blur. These are again consistently and strongly biased toward more blurred images, indicating that under adaptation to blurred images the original images again appeared too sharp. The Gaussian blur still does not simulate the effects of actual refractive errors, and in particular does not correctly simulate the changes in image contrast. Nevertheless, the results of Figures 3 and 5 suggest that the after-effects are not critically dependent on the specific form of image filtering, and thus are likely to capture the basic adaptation effects that should arise from refractive errors. To estimate these, we compared the appearance of the filtered images to the original images defocused by viewing the display through trial lenses. The best-matching refractive errors corresponded to a variation from roughly 0.25 diopters to more than 6 diopters of defocus (for the weakest to strongest adapting blurs). This comparison suggests that the degree to which adaptation compensates for the perceptual consequences of refractive errors is substantial. For example, after only a few minutes of adaptation to a moderately blurred image (e.g. s.d. = 4), the image that appeared in focus had a blur s.d. of ~1.2, suggesting that adaptation would greatly reduce the degree to which the world actually *appeared* blurred because of optical defocus. (On the other hand, larger adapting blurs do not have correspondingly stronger effects on perceived focus and instead are somewhat weaker. We argue below that this is probably because the adapting spectra are shifted too far from the frequency range on which perceived focus depends.)

We have assumed that these spatial after-effects reflect cortical mechanisms of contrast adaptation, but an alternative possibility is that they are a simple artifact of retinal light adaptation. After viewing the static adapting images, a negative afterimage was often visible in the interval before the test stimulus, and was particularly strong for the blurred adapting images. This blurred negative afterimage might combine with the positive test image to partially cancel the lower spatial



32 16 8 4 2 1

Figure 4. An example of the images generated by Gaussian blur. Numbers below each image indicate the standard deviation of the Gaussian point spread function in image pixels (equal to 1/64th the value in degrees visual angle).

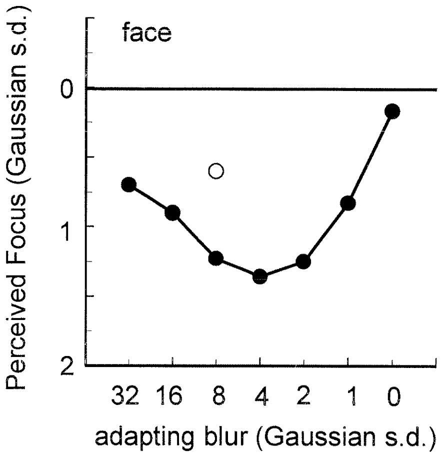


Figure 5. Shifts in the perceived focus of images following adaptation to Gaussian blur. Filled circles plot the standard deviation of the blurring that appeared best focused as a function of the standard deviation of the adapting blur for the face image (both in units of image pixels). The unconnected, unfilled circle shows settings for the blurred adapting image with s.d. = 8 but with the contrast polarity inverted, included to test for the effects of light adaptation.

frequencies, so that the original image appeared sharper. This account is less plausible for the sharpened adapting images, since the features in this case are more likely to be smeared by eye movements and any afterimages from them are less likely to be in proper register with the test stimulus. Nevertheless, to test for this possibility we also measured the after-effects for contrast-reversed adapting images. The results for this control run are shown by the unfilled circle in Figure 5, following adaptation to the "negative" of the stimulus with a blur s.d. of 8. The test stimuli were again positive images. In this case the afterimage for the negative adapting stimulus had the same polarity as the test stimuli, and thus should have caused the original test to appear too blurry. Yet the focus point is again shifted in the same direction (toward blur, indicating that the original again appeared too sharp). Thus light adaptation is unlikely to be the major basis for the blur adaptation effects. On the other hand, as Figure 5 suggests, the after-effects were somewhat weaker when the adapting and test images had different polarities than when they were the same. This could reflect a marginal contribution from light adaptation, though this difference is also consistent with contrast adaptation effects that are selective for contrast polarity[25, 26]. The latter possibility is

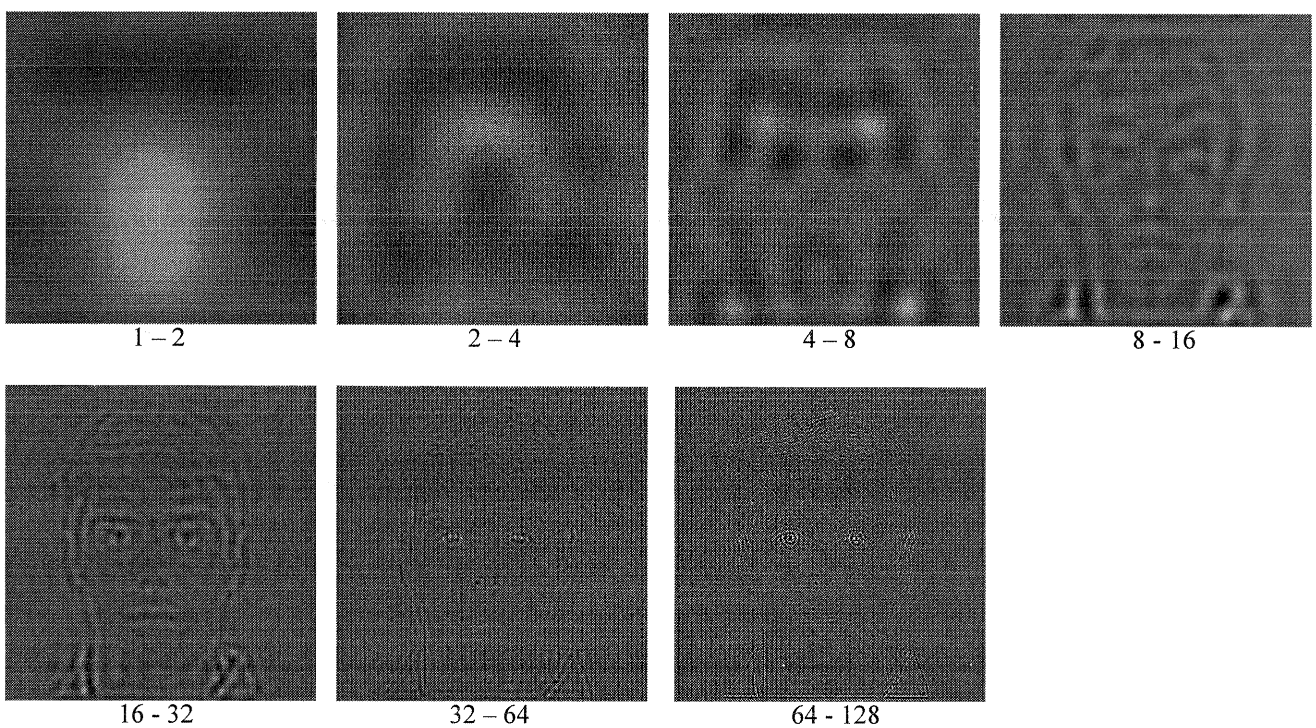


Figure 6. Examples of the images used for bandfiltered adapting stimuli. Images show the original face image filtered into successive 1-octave bands, with the cutoff frequencies in cycles/image (equal to 4 times the frequency in cycles/degree) listed below each picture. Contrasts for the highest frequency image have been accentuated so that the structure is more visible in the figure.

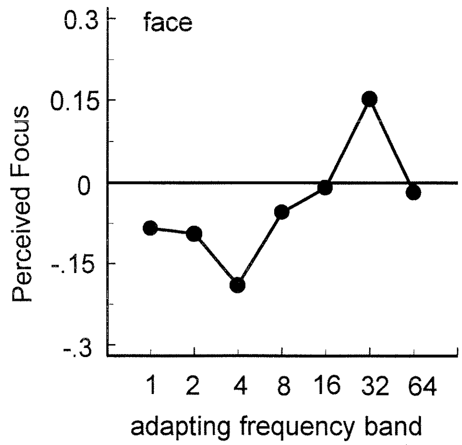


Figure 7. Shifts in the perceived focus of the face image after adapting to band-filtered versions of the test image. Values show the slope of best perceived focus as a function of the lower cutoff frequencies of successive 1 octave bands (in cycles per the 4-deg image).

supported by additional procedures we added in the final experiments (described below) to further control for light adaptation. In these, we modified the display so that the adapting stimulus was shown within a 6-deg square window, demarcated by narrow black borders. The 4-deg image within the window was randomly repositioned every 250 ms during adaptation, so that the local light and contrast adaptation effects were roughly constant. In these cases afterimages were rarely visible, while the magnitude of the after-effects was similar to that for the static adapting images. Thus this again suggests that the after-effects are primarily if not completely the result of contrast adaptation.

The preceding results show that tilting the overall spectrum of the image toward lower or higher frequencies induces adaptation to blur or sharpness, respectively. But within this context what do "lower" and "higher" correspond to? In the next experiment we asked which specific frequency components in the stimulus contribute to the perception of blur versus sharpness. To explore this we used the same test stimuli, but this time examined the consequences of adapting to images that were filtered into a narrow range of frequencies. Figure 6 again shows the set of adapting stimuli for the face image. The series shows the original image filtered into successive 1-octave bands. (For the figure, contrasts for the highest frequency image have been boosted so that features are visible, though in the actual images contrasts were not renormalized after filtering.) Figure 7 shows the shifts in perceived focus as a function of the adapting band. These results should be interpreted with caution since the adaptation effects at different frequency ranges are probably not independent[24]. However, they suggest that the effects of adaptation on the perceived focus point may depend on a fairly restricted range of frequencies. Specifically, adapting to the 4-8 cycles/image band (1-2 cycles/deg) produced the strongest biases toward sharper images, while the 32-64 cycles/image band (8-16 cycles/deg) induced the largest shift toward blurrier images. Notably, the effects were much weaker for the spectral extremes, consistent with the weakened effects observed for the strong Gaussian blur in Figure 5. These frequency bands ostensibly represent the most strongly blurred or sharpened images, but as adapting stimuli may be too far removed (or in the case of the high frequencies, too low in effective contrast) to alter sensitivity to the mid-range frequencies that appear to dominate the judgments. Also notably, adaptation to the 16-32 cycle/image band (4-8 cycles/deg) had little effect, presumably because this image produced equivalent sensitivity changes at lower and higher frequencies. This band thus appears to delineate the shift from lower to higher frequencies in the adaptation effects for this image.

In the last set of measurements we examined how selective the blur after-effects are for the specific images that the observer is adapted to. The effects of contrast adaptation are typically strongest when adapting and test images are similar, and may show only minimal transfer across very different stimuli. (In fact, for this reason they are also often referred to as pattern-selective after-effects[13].) For example, adapting to a vertical grating has only weak effects on sensitivity to horizontal gratings[14-16], and thus we might expect little transfer of the blur after-effect across images that contained large orientation differences. On the other hand, natural images typically contain a broad range of orientations and have similar amplitude spectra, and thus it is not certain to what extent these common attributes would induce common adaptation states, or to what extent the adaptation is controlled by other dimensions along which the images differ. To explore this, we adapted to blurred or sharpened versions of one image and then set the perceived focus for the same or different images. Stimuli included the five images shown in Figure 1. As noted above, during adaptation the observer viewed a single image whose position was randomly jittered over time, to try to equate both light adaptation and contrast adaptation for different regions of the retinal image. Tests were displayed in the center of the adapting window. During a single run settings were made for each of the five test images shown in five randomly interleaved staircases.

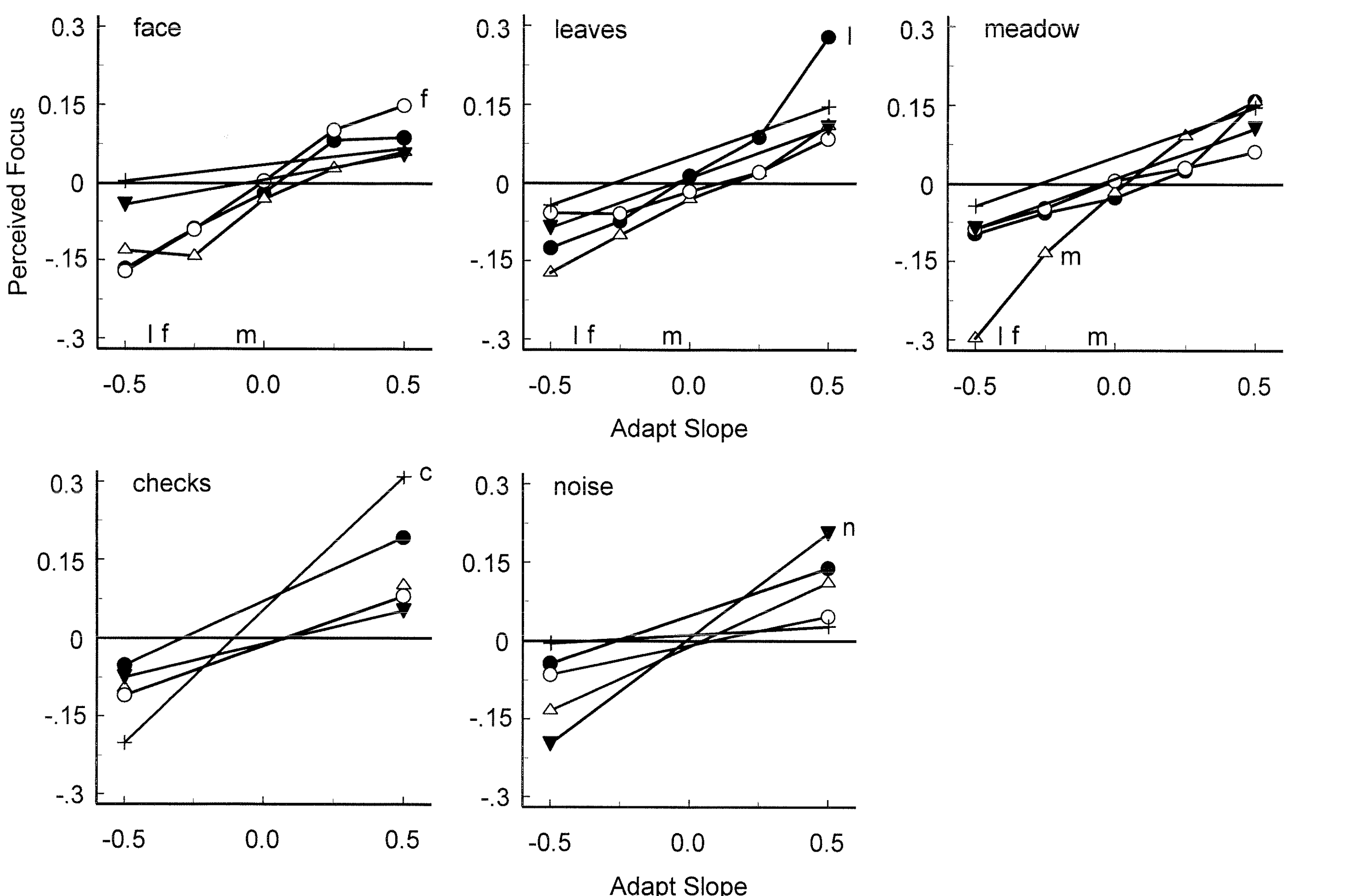


Figure 8. Measurements of the selectivity of the blur adaptation for different images. Each panel plots the effects of a single adapting image on the perceived focus of each of the five test images shown in Figure 1, as a function of the adapting slope. Letters by curves mark settings when test and adapt images were the same. Letters along the x axis indicate the effective slopes of the three focused natural images, relative to a nominal slope of –1.

Figure 8 shows the biases induced in the test images after adapting to different images. Each panel plots the results for a single adapting image, with the spectral slope filtered by –0.5 or +0.5. Two features are apparent in these results. First, there is substantial transfer of the adaptation across different images, and in particular across the different natural images. Thus in the course of natural viewing it is likely that the effects of blur adaptation (e.g. owing to a refractive error) would largely generalize across successive views. In fact, this was also apparent in the course of running the experiment. For example, after adapting to any of the sharpened images, the text displayed at the conclusion of the run was often uncomfortably blurred. On the other hand, the biases in perceived focus were in most cases strongest when the adapting and test images were the same. Thus the sensitivity losses do not depend simply on image blur per se, but must also reflect adjustments that show some selectivity for other aspects of the stimuli. Unfortunately, the present results do not reveal what aspects these might be, since the images were chosen only to reflect qualitatively different classes of stimuli.

For the three natural images, we also made additional measurements of the cross-adaptation effects, following adaptation to the original image or to the images with slopes filtered by $\pm$0.25. These were included to test to what extent the adaptation depended simply on the amplitude spectra of the images. As noted, natural images vary significantly in their spectra, with slopes for individual images typically ranging from –0.5 to –1.5[2-8]. The slopes for the natural images we tested are shown along the x axis of Figure 8, and were –1.35 (face), -1.39 (leaves) and –1.07 (meadow). Thus the face or leaves had slopes that were (in terms of the averaged amplitude spectrum) equivalent to a moderately blurred (~-0.3) version of the meadow, and adaptation to them could potentially have induced after-effects similar to those induced by blurring the meadow. However, we instead found that adaptation to any of the original images did not systematically bias the perceived focus of other images, and that the effects of adapting to the filtered images were in each case similar. Thus the after-effects cannot be predicted from a global measure like the overall amplitude spectrum. Field and Brady[1] noted that the slope of the amplitude spectra of images could vary either because of differences in the amount of structure at different spatial scales or because of differences in the relative contrast at different scales. It is the latter variation that primarily determines whether an image appears blurry or sharp, and our results suggest it is this variation that primarily determines the adaptation.

4. DISCUSSION

As noted in the Introduction, Webster and Miyahara[8, 24] previously explored adaptation to the spatial structure of natural images by measuring how adaptation alters threshold contrast sensitivity. The present results support the conclusion that adaptation plays an important role in regulating spatial sensitivity in natural viewing, and provide a more striking demonstration of these adaptive adjustments. In particular, the after-effects of adaptation on perceived blur appear much more conspicuous and much more sensitive to changes in adaptive state than would predicted by the changes that the same adaptation induces in contrast thresholds. For example, in our previous work[8, 24] we found that filtering images by slopes of ± 0.5 or blurring images by 1-2 diopters did not lead to significantly different adaptation effects on the contrast sensitivity function, yet biases of the same magnitude have marked effects on the present suprathreshold measures of perceived blur. This difference is somewhat surprising because contrast adaptation effects tend to be weaker on higher-contrast test stimuli[13, 27, 28], and thus might reasonably be expected to be more pronounced at threshold. However, there are two likely bases for the larger effects in the present case. First, the thresholds were measured for simple sinusoidal test gratings while the adaptation was to complex naturalistic stimuli. As Figure 8 shows, the after-effects of the adaptation are selective for spatial properties of the stimuli, and thus may have been substantially weaker when measured on the test gratings. An important advantage of the present measurements is that they examine the consequences of natural image adaptation *on* natural images. A second reason is that compared to contrast thresholds, judgments of image blur are very frequent and important in natural viewing. Thus the stimulus attribute of blur is one that observers may be especially sensitive to, so that even small changes are highly salient. Indeed, slope changes of less than 0.1 could be readily measured for the blur after-effects, while biases of similar magnitude would be difficult to resolve in the contrast sensitivity function. In this sense, blur perception may be similar to human face perception, in which small physical differences (e.g. in facial configuration) are important and must regularly be discriminated, and thus are again differences to which the visual system may be well tuned[29]. Like blur perception, adaptation also has pronounced effects on face perception – inducing figural after-effects that markedly change the appearance of faces[30, 31] – and the salience of these after-effects probably depend in part on the special sensitivity that observers have for these stimuli.

A second notable way in which the blur settings differ from our threshold measurements is with regard to the biases relative to neutral (uniform field) adaptation. Webster and Miyahara[8, 24] found that adapting to natural images selectively reduced sensitivity at low to medium spatial frequencies, and attributed this to the low-frequency bias (~1/f) characteristic of the image spectra. However, this aspect of the adaptation is not apparent in the present settings. Specifically, adapting to a focused image does not obviously cause the image to appear sharper, as the threshold changes might predict (though adapting to defocus does in fact appear to improve visual acuity[32]). This difference could result either because perceived blur depends on different processes than simply relative contrast at different scales (see below) or because the adaptation effects for simple gratings cannot be generalized to more complex test stimuli (for which there is substantial evidence[24]). The question of what constitutes a neutral state for the spatial adaptation is an important one, because it depends on the intrinsic spatial sensitivity of the visual system. As we noted in the Introduction, the receptive fields of visual cells appear matched to the 1/f structure of natural images, so that response amplitudes are similar across different spatial scales[4]. To the extent that the visual response is already matched to the stimulus, adaptation should not induce a response bias – or in other words should not alter the response *selectively*. On the other hand, these selective changes may be the very process by which the visual system fine tunes the match to the visual world, so that it is difficult – or perhaps even meaningless – to try to assess the "pre-adapted" sensitivity. These adaptation processes may adjust both to short-term changes of the kind our experiments address, and much longer term changes that commonly arise in the case of refractive errors or changes during visual development. For example, Fine, Smallman, and MacLeod[33] have recently examined the spatial sensitivity of an individual following removal of cataracts. For this subject the world appeared overly sharpened – even weeks after his surgery – and they attributed this to very long-term adaptation to blur induced during his vision with cataracts.

What specifically is being adapted when the visual system is presented with a blurred image? Our present results only hint at the possible stimulus selectivities, but one important property we have shown is that the adaptation does not depend simply on the overall amplitude spectrum of the stimuli. That is, at least with regard to perceived blur, there appears to be little cross adaptation between different focused images, even though these images differ substantially in their spectral slopes. This is consistent with the finding that different images appear focused when they have appropriate contrasts at different spatial scales, even though they may have different amplitude spectra because they differ in the number of edges at different scales[1]. That the adaptation to blur behaves similarly suggests that the visual system is adjusting sensitivity to equate amplitude independently of the density of structure at different scales, and thus is not adjusting merely to the overall contrast variation across frequency. Moreover, from the perspective of a single cell sampling different regions of the image during eye movements, it suggests that the adaptation depends on the absolute amplitude of the presented stimulus, rather than on the set of contrasts averaged over time. This raises the possibility that blur is coded more as an explicit feature of the image than as an implicit property (i.e. as a property that is represented only indirectly through the explicit coding of contrast at each scale). And given the high sensitivity to this feature and its importance for vision, it is tempting to draw again from the analogy with face perception to suppose that there may be special mechanisms for detecting blur, and that adaptation serves to normalize the response for these "feature detector."

4. ACKNOWLEDGMENTS

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