

Contrast sensitivity under natural states of adaptation

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ABSTRACT

The contrast sensitivity function (csf) is central to describing spatial vision and to models of visual coding, yet little is known about the form of the function under natural viewing conditions. We examined how contrast sensitivity is affected by adaptation states that should arise in the course of normal viewing. Webster and Miyahara³² showed that adaptation to the low-frequency ($\sim 1/f$) biases in natural scenes selectively reduces sensitivity at low frequencies. Here we examine how these sensitivity changes depend on the properties of observers, by varying subjects' refractive state or by measuring adaptation to chromatic contrast rather than luminance contrast. Defocus and physical blurring have similar effects, altering the adaptation only for strongly blurred images. Switching to chromatic contrast induces larger sensitivity changes at low frequencies, consistent with the different csf's for color and luminance. Thus natural viewing may lead to characteristic adaptation states that differ for luminance and color. To examine the basis for these sensitivity changes, we adapted to $1/f$ patterns filtered over different frequency bands. Adding lower frequencies to images reduces the adaptation induced by higher frequencies. Thus in natural-image adaptation, the low-frequency bias may result - not from the bias in the input spectra - but because the adaptation at different spatial scales is not independent.

keywords: spatial vision, contrast sensitivity, contrast adaptation, natural images, natural scene statistics, luminance, color, refractive errors, spatial frequency, spatial-frequency interactions

1. INTRODUCTION

Measures of visual sensitivity are fundamental to modeling human vision and predicting visual performance. We have examined how sensitivity depends on the states of contrast adaptation that are likely to be induced by the natural visual environment. Contrast (pattern-selective) adaptation adjusts sensitivity according to the prevailing patterns of spatial, temporal and chromatic variations in the stimulus³⁰. The changes in sensitivity are manifest in a variety of related after-effects, including changes in detection thresholds^{4, 6}, in the apparent contrast of suprathreshold patterns^{5, 12}, and in the perceived structure of patterns (e.g. as in the after-effects of perceived tilt¹³, motion³⁷, or color³³). Strong after-effects can occur even for brief stimulus exposures, suggesting that - like light adaptation (to the mean luminance and color in scenes) - contrast adaptation (to the patterns in scenes) plays a constant role in regulating our perception. Thus contrast adaptation effects are likely to be important to any complete characterization of visual sensitivity. Yet how adaptation might shape visual sensitivity under natural viewing conditions has received little attention.

In a recent series of studies, we examined the sensitivity changes induced by adaptation to the chromatic or spatial structure of natural images^{31, 32, 34-36}. The sets of colors in natural scenes are highly restricted, and show strong biases along only a limited range of axes within the volume of color-luminance space^{8, 22, 34}. Webster and Mollon³⁴ showed that adaptation to natural color distributions can strongly alter color appearance by selectively reducing sensitivity to the dominant color-luminance axes of the distributions. With regard to spatial structure, a number of studies have noted that the second-order statistics of natural images have a characteristic form, with amplitude spectra that fall with frequency roughly as $1/f$ (corresponding to a spectral slope (α) of -1 on a plot of log amplitude vs log frequency)^{8-10, 21, 27, 28, 32}. Webster and Miyahara³² measured how adaptation to natural scenes affected spatial sensitivity, by comparing the threshold contrast sensitivity function (csf) and suprathreshold apparent contrast, after adapting to ensembles of natural scenes or to a uniform (zero-contrast) field. Adaptation to natural images - which have a strong low frequency bias - reduced sensitivity at low to medium spatial frequencies but had little affect at higher frequencies, and thus altered the effective shape of the csf. The

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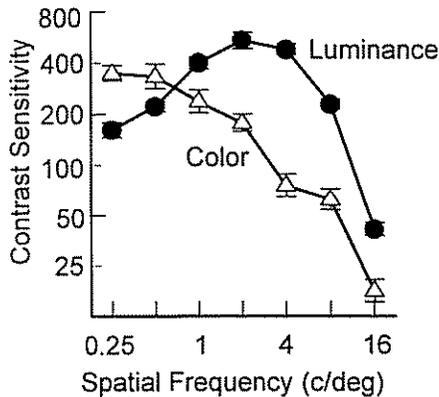


Figure 1. Spatial contrast sensitivity functions for luminance contrast (circles) or L-M chromatic contrast (triangles). The csf's were measured under neutral (zero-contrast) adaptation, and show characteristic bandpass (luminance) or lowpass (chromatic) tuning. Observer MW.

sensitivity changes were similar for very different image sets, including a range of different outdoor scenes and synthetic noise images that were filtered to have $1/f$ spectra. Moreover, after-effects for image sets with different spectral slopes were roughly similar within the range of slopes reported for natural scenes (~ -0.5 to -1.5), and differed only for highly blurred or whitened images. These results thus suggested that the common spatial structure of natural scenes may tend to maintain the visual system in a common state of spatial contrast adaptation, characterized by reduced threshold sensitivity at low to medium spatial frequencies. (Because the adaptation was to ensembles of images, the measured sensitivity changes presumably do not reflect stimulus characteristics specific to individual images, such as the phase structure. Webster and MacLin³¹ examined figural after-effects in the perception of human faces, and showed that adaptation to individual natural images like faces can produce large changes in spatial perception that are strongly selective for the specific adapting image. The measurements also do not address variations in the mean contrast across different scenes, which may be pronounced under different viewing conditions.)

In the present study we further examine the effects of natural image adaptation on spatial contrast sensitivity. A first goal of the study was to explore further the range of adaptation states expected for natural viewing conditions. As noted, Webster and Miyahara³² found that different stimulus sets apparently did not vary enough in their second-order statistics to induce qualitatively different patterns of adaptation. However, the effective stimulus for contrast adaptation should depend on both the physical image and the “filtering” properties of the observer. Here we examine two ways in which the properties of observers may vary. First, we asked how the adaptation might depend on blurring the retinal image owing to refractive errors. Because blur selectively attenuates the higher frequency components, it is roughly similar to increasing the spectral slope of the image. For example, Tadmor and Tolhurst²⁴ noted that a $+1.5$ D defocus was roughly equivalent to changing α by -0.5 , shifting $1/f$ images close to the limit of the range measured for different natural scenes (-1.5). Thus even moderate accommodative errors may be sufficient to substantially alter the effective structure of the scenes, and we asked whether such errors may as a consequence measurably alter the observer’s state of adaptation. Such effects are relevant to understanding natural states of adaptation both because many parts of the visual field will often be out of focus, and because refractive errors are widespread. Moreover, Mon-Williams et al.¹⁷ have recently reported improvements in visual acuity following optical defocus, and have attributed this to changes in the state of adaptation under defocussed viewing.

A second way in which we examined variations in the properties of the observer was to examine the adaptation effects for chromatic contrast rather than luminance contrast. The slopes of the amplitude spectra of natural scenes have been found to be similar whether measured for luminance variations or chromatic variations^{20, 22, 34}. However, the spatial sensitivity of the visual system is very different for luminance and color¹⁸. For example, Figure 1 compares the csf for luminance or chromatic (reddish-greenish) gratings. While the luminance csf is bandpass, the chromatic csf is instead lowpass. Consequently the low-frequency bias in natural images might prove especially potent for adapting mechanisms sensitive to chromatic contrast, and we therefore asked whether natural images might induce different patterns of adaptation for luminance and color sensitivity.

A further goal of the present study was to examine the actual nature of the spatial adaptation effects. A selective loss in threshold sensitivity at low to medium frequencies might seem readily consistent with the low-frequency bias in images, yet for a number of reasons the form of the sensitivity losses are not straightforward to predict. First, the low-frequency attenuation in the luminance csf may tend to compensate for the increased power at low frequencies in images, so that the



Figure 2. Examples of images from the meadow, forest, or close-up sets of natural scenes.

neural image (i.e. the product of the stimulus and filter spectra) is effectively whitened^{1, 23, 29}. Second, receptive fields in the visual cortex – the earliest locus of the contrast adaptation effects – have spectral bandwidths that increase with preferred frequency¹⁰. Thus high frequency cells may integrate energy over a wider spectral range. In this way the cells might be roughly matched to the $1/f$ spectra of images, so that the distribution of responses is roughly independent of frequency^{7, 11}. Given such models, the low-frequency bias in the adaptation effects is in fact surprising. However, this comparison assumes that the adaptation effects at different spatial scales are independent. Studies of adaptation with simple compound stimuli, composed of pairs of gratings that differ in orientation or spatial frequency, have instead found strong interactions between the after-effects induced by different components^{14, 15, 19, 25, 26}. For example, Tolhurst²⁵ and Nachmias et al.¹⁹ observed that adaptation to a grating with spatial frequency of 3F was stronger when it was presented in isolation than when it was paired with a grating of 1F. The low frequency component therefore “inhibited” the adaptive influence of the higher harmonic. We asked whether similar interactions might underlie the pattern of adaptation effects for natural images, by comparing the after-effects for images highpass filtered over different frequency ranges.

2. METHODS

Stimuli and procedures were similar to those reported in Webster and Miyahara³², and are described there in detail. Briefly, adaptation effects were measured for two types of adapting stimuli: outdoor scenes that lacked obvious human influence, and synthetic images derived from filtered noise. The natural scenes were taken in mountain regions near Reno, Nevada, with a Kodak DCS420IR monochrome digital camera (with added IR filter), and were linearized through an empirically defined gamma correction. The scenes were used to define three groups (16 each of meadows, forests, or close-ups) that varied in viewing distance and subject matter (Figure 2). The full set of images had an average rms contrast of 0.784 and mean α of -1.13, values that are comparable to previous estimates for natural scenes. All images were adjusted to have the same mean luminance. To create the filtered noise stimuli, white-noise images were generated from different sequences of random normal deviates. The image amplitude spectrum was multiplied by f^α , with the value of α ranging from 0 to -2.5 in 0.5 steps (Figure 6). The images were adjusted to have the same mean and an rms contrast of 0.35 (near the limit for avoiding significant pixel truncation). For the final experiment, the images with slopes of -1 were further filtered to remove all frequencies below a specified cut-off frequency, forming 6 groups of images with cut-offs ranging from 0.5 to 16 c/deg in 1 octave steps (Figure 10). For this group image contrasts were not renormalized after filtering.

Stimuli were displayed on a Sony Trinitron Multiscan 20se monitor controlled by a Cambridge Research Systems VSG graphics board. The adapting images were presented through an 8-bit framestore. Test stimuli were horizontal sinewave gratings, and were presented through a 14-bit waveform generator windowed by the framestore. Grating frequency ranged from 0.25 to 16 c/deg. Outputs of the framestore and waveform generator were linearized through separate gamma corrections and were closely matched for mean luminance (12 cd/m² for the natural images or 30 cd/m² for the noise images) and chromaticity (equivalent to Illuminant C), based on calibrations with a PhotoResearch PR650 spectroradiometer.

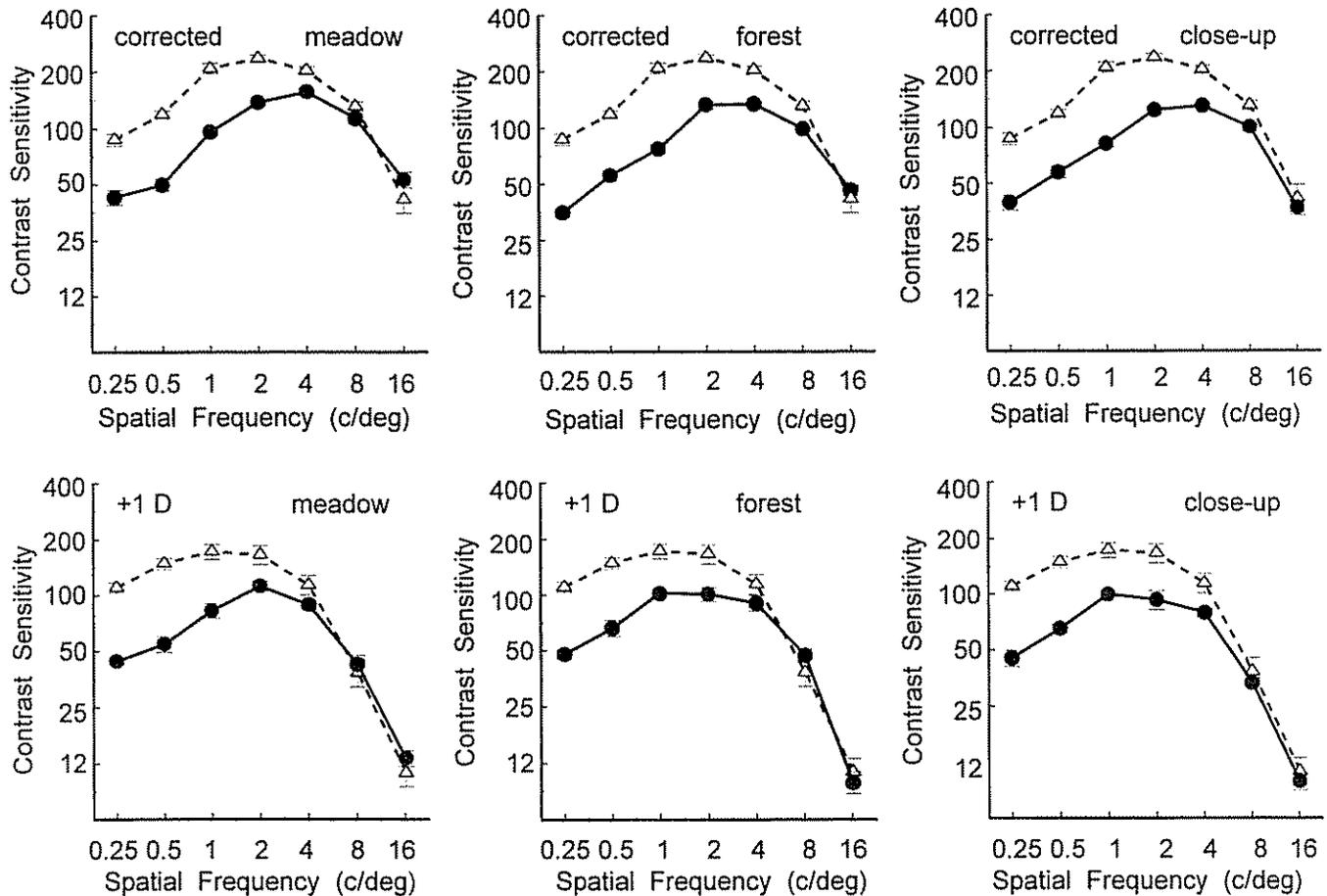


Figure 3. CSF's for small refractive errors. Panels plot the luminance csf measured before (triangles) or after (circles) adaptation to different natural image sets. For each image set the two panels show measurements made with corrected acuity (top) or an uncorrected error of +1 D (bottom row). Observer EM.

To create chromatic images, look-up tables were used to remap luminance values in the filtered noise images to variations in chromatic contrast. Stimuli were varied along the two chromatic axes of the MacLeod-Boynton¹⁶ chromaticity diagram, which correspond to opposing signals in the long and medium wavelength sensitive cones (L-M) or to signals in the short wavelength (S) cones opposed by the combined signals in the L and M cones [S-(L+M)]. These two axes are thought to be central to the organization of color at early post-receptoral levels of the visual system³⁰. Contrast along each axis was arbitrarily scaled to equal 1.0 at the maximum complementary color excursions possible for the display, and equiluminance was defined photometrically. The resulting stimuli had MacLeod-Boynton coordinates of (0.6568, .01825) at the mean (Illuminant C) chromaticity and maximum excursions of (0.7117, .01825) for the +L-M axis and (0.6568, .03388) for the +S-(L+M) axis.

Stimuli were presented in a square field in the center of the display. For the experiments on refractive errors and color contrast, the field subtended 5.6 deg and was set apart by narrow black borders from an 8 by 10.5 deg background of the same mean luminance and chromaticity. Adapting images displayed in the field contained frequencies ranging from 0.149 to 19.1 c/deg at the 200 cm viewing distance. For the third experiment, on frequency interactions, we increased the viewing distance to 335 cm and altered the field size to 4 deg, in order to confirm the adaptation effects for higher image resolutions. The images in this case contained frequencies ranging from 0.25 to 32 c/deg.

Observers viewed the display binocularly in an otherwise dark room. Each run began with an initial 5-min period of adaptation. During adaptation the observer viewed a rapid and random sequence of images drawn from one of the natural image sets or filtered noise sets. We chose to adapt always to sets of images so that the adaptation would reflect the average stimulus properties for the adapting ensemble. The displayed image was resampled at random every 300 ms. This was chosen

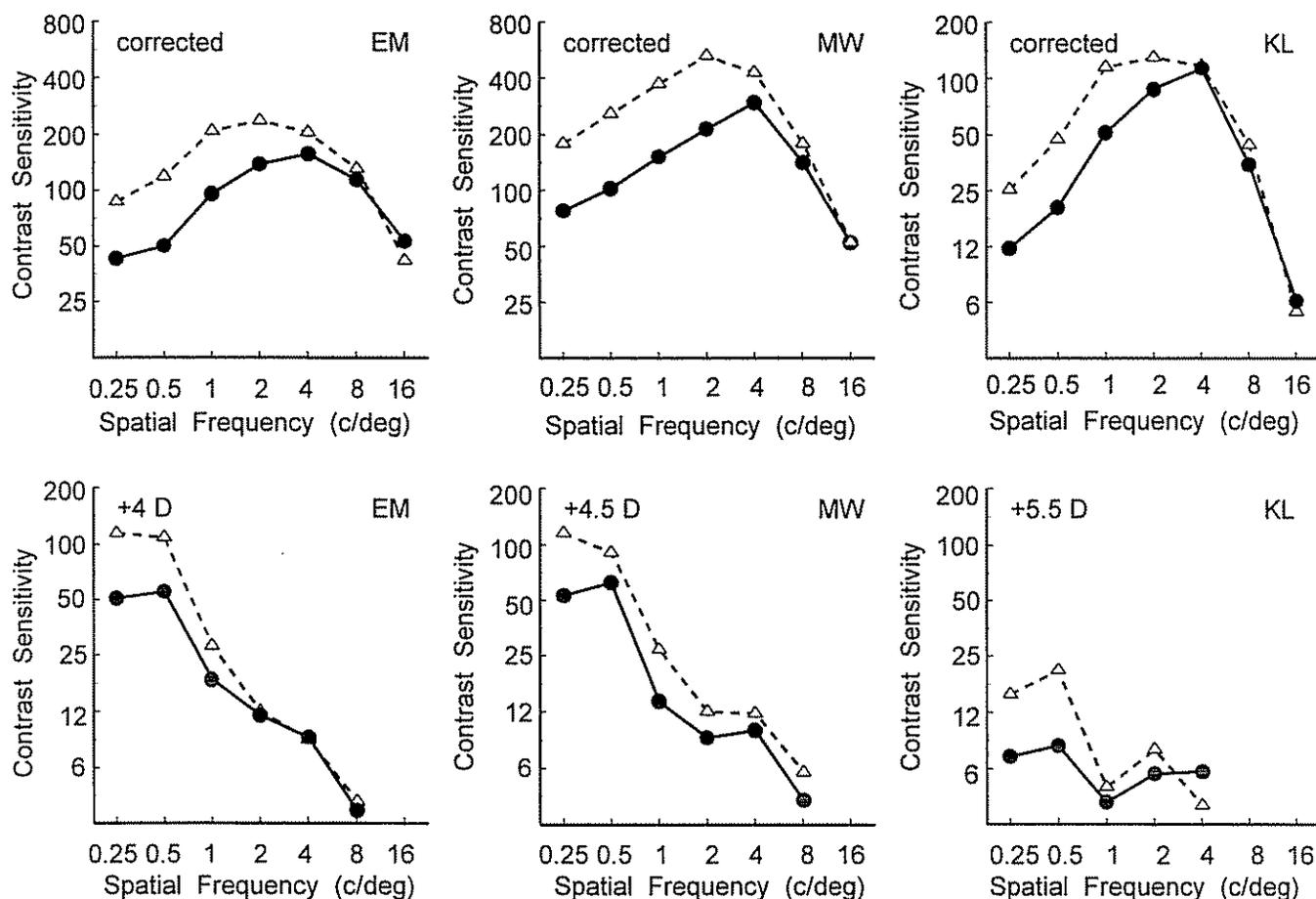


Figure 4. CSF's for large refractive errors. Panels plot the luminance csf measured before (triangles) or after (circles) adaptation, for three different observers. For each observer the two panels show measurements made with corrected acuity or a refractive error of +4 D (EM), +4.5 D (MW) or +5.5 D (KL).

to minimize local light adaptation to individual images and to try to simulate the pattern of stimulation that might arise from rapid and random eye movements within the image ensemble. Following the initial adaptation, a test grating was presented for 700 ms, with contrast ramped on and off during the first and last 150 ms with a Gaussian envelope ($\sigma = 50$ ms). Test presentations were interleaved with 6-sec re-adaptation intervals, with 500 ms zero-contrast gaps before and after each test. This sequence continued throughout the run while observers set thresholds by using a button-box to adjust the contrast of the test grating. During a run thresholds were set once for each test frequency, in counterbalanced order, with 6 to 8 runs for each daily session. Adapting sets were constant within each session, with different sets counterbalanced across sessions. The post-adapt results presented are each based on the average of 6 to 12 settings per frequency. Each session also included 1 or 2 initial runs in which pre-adapt thresholds for each frequency were measured. For these runs the adapting field remained at zero contrast but the testing sequence was otherwise identical to post-adapt trials. Results presented for the pre-adapt contrast sensitivity are based on the mean of 6 to 14 runs averaged across the different sessions. Observers included the author and four additional observers. The observers had normal (MW) or corrected-to-normal (EM, KL, JR and VR) visual acuity.

3. RESULTS AND DISCUSSION

3.1. Refractive errors

Figure 3 shows the effects of modest refractive errors on the csf before and after adaptation to natural images. The observer (EM) had a spectacle correction of -1 D. The top row shows the csf's measured with the corrected refraction, and are replotted from Webster and Miyahara³². The bottom row shows results when the measurements were instead made without

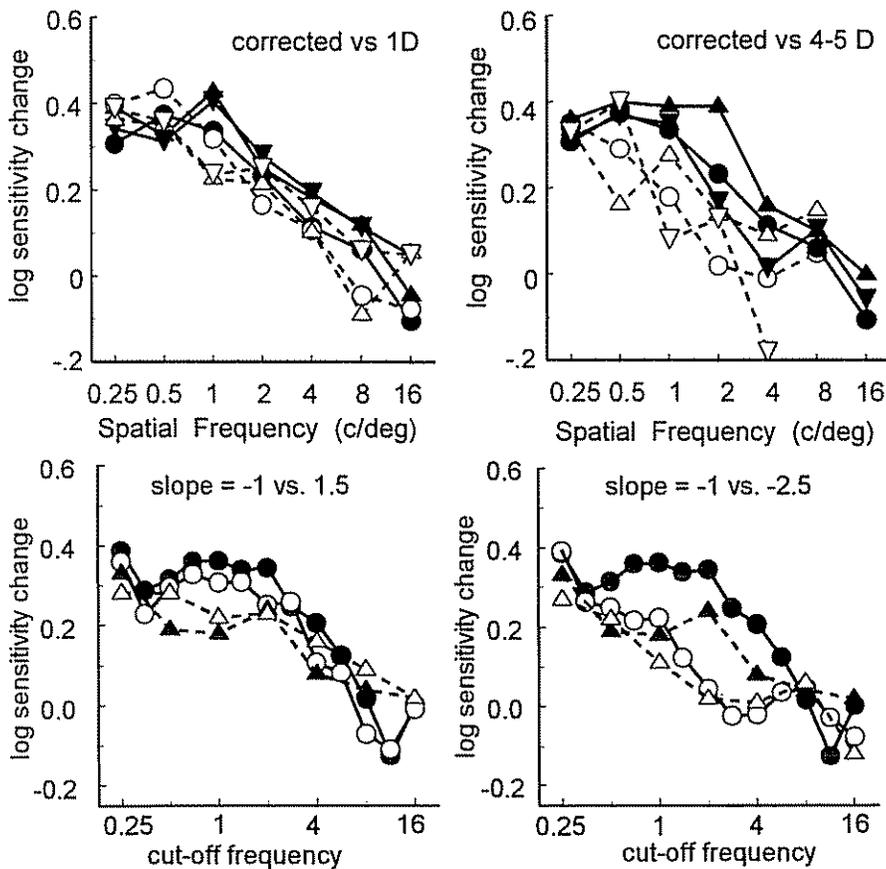


Figure 5. Comparison of adaptation effects for small (top-left, from Figure 3) or large (top-right, from Figure 4) refractive errors. Plots show the log change in threshold sensitivity for the focussed (filled symbols) or defocussed (unfilled symbols) viewing conditions. Bottom panels show similar comparisons for small (-1 vs. -1.5, bottom-left) or large (-1 vs. -2.5, bottom-right) changes in the spectral slopes of the adapting images (from Webster and Miyahara³²). Plots show the sensitivity changes for $1/f$ (filled symbols) or blurred (unfilled symbols) adapting images for observers MW (circles) or EM (triangles).

glasses. The three columns plot the results for the three different adapting image sets shown in Figure 2. As we noted, the after-effects for the different image sets are very similar, all inducing losses in sensitivity at low to medium spatial frequencies while producing little change at the highest frequencies. Without her correction the csf shows moderate sensitivity losses at higher frequencies, but the effects of adaptation appear similar. This comparison is shown directly in Figure 5 (top-left panel), which plots the adaptation effects (log change in sensitivity) for the refracted vs. unrefracted conditions. The two sets of tuning functions largely superimpose, suggesting that moderate variations in refractive state - like moderate variations in the image spectra - are not sufficient to alter significantly the shape of the csf through contrast adaptation (though defocus may alter adaptation in ways our measurements do not capture¹⁷).

Figure 4 shows the effects of more extreme refractive errors. For EM the measurements were made by viewing the display through +3 D trial lenses (giving a total error of +4 D). MW is emmetropic and made settings with or without +4.5 D lenses. Finally, KL wears a spectacle correction of -5.5 D and made settings with or without her glasses. In this case there are of course very pronounced changes in sensitivity owing to the defocus, with the csf's becoming lowpass. The adaptation effects are again confined to lower frequencies, but may now be weaker for the blurred conditions. This difference is shown in the top-right panel of Figure 5, which again plots the threshold changes for the focussed vs. defocussed viewing conditions. The comparison shows modest but consistently weaker adaptation effects for the blurred images at moderately low frequencies.

In Figure 5, these effects of refractive errors on adaptation are compared to the effects of changes in the spectral slopes of the adapting images. As noted, Webster and Miyahara³² found that similar sensitivity changes were induced by adapting stimuli with slopes varying from -0.5 to -1.5, the range reported for different natural scenes. This is shown in the bottom-left panel, which compares the threshold changes for filtered-noise image sets with slopes of -1 vs. -1.5 (see Figure 6). The present results suggest that the after-effects will also remain similar despite modest refractive errors, again suggesting that adaptation to the world may tend to maintain the csf in a fairly stable state over a wide set of viewing conditions. Alternatively, the effects of large refractive errors appear to parallel the effects of large changes in the amplitude spectra, as shown in the bottom-right panel comparing the threshold changes for images with slopes of -1 vs. -2.5. Such strongly blurred images are

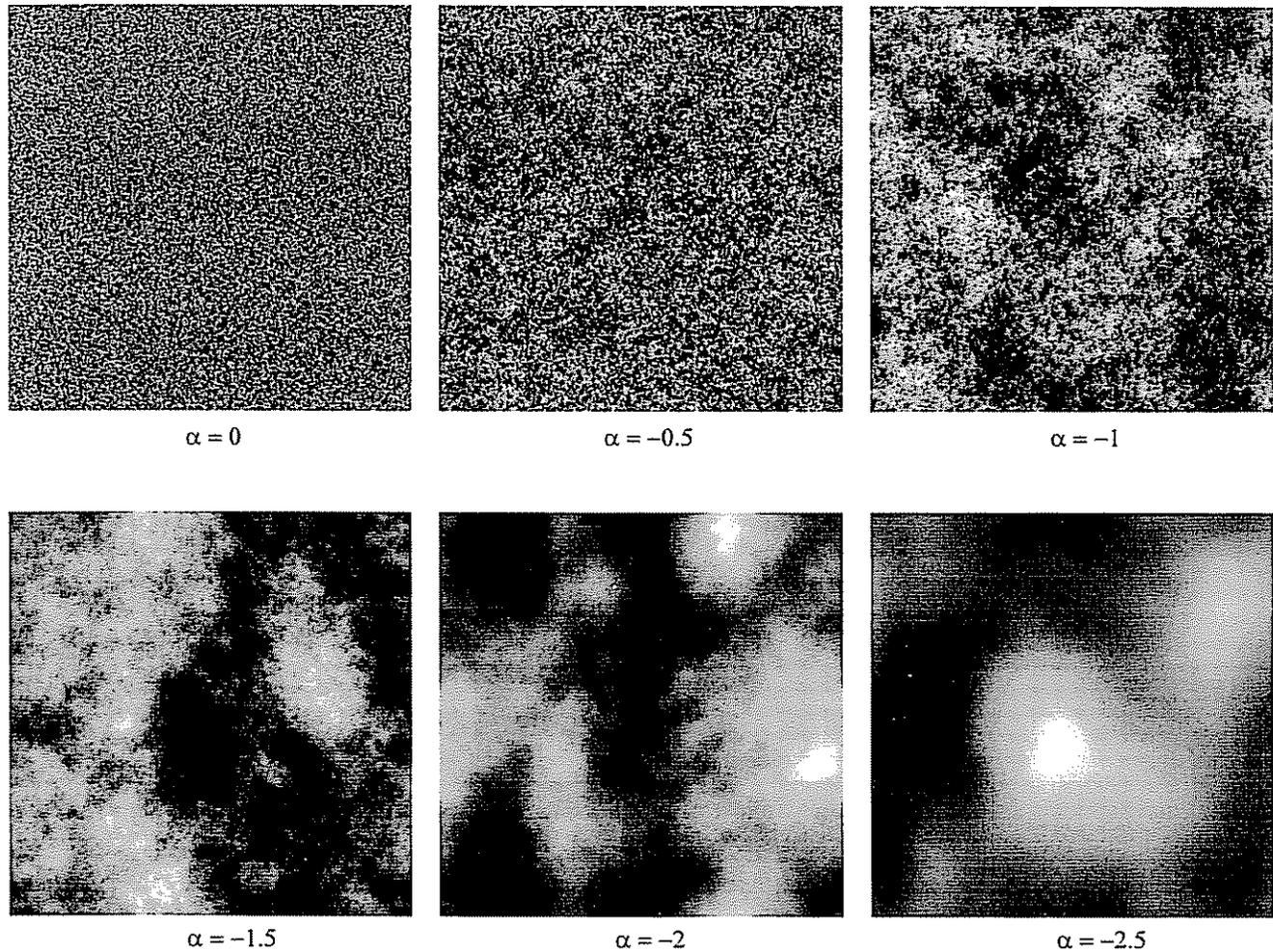


Figure 6. Examples of the filtered noise images used for comparing the spatial adaptation effects for luminance or chromatic contrast. Images were composed of white noise filtered over a range of spectral slopes from 0 (unfiltered) to -2.5 (strongly blurred). Images were varied in luminance contrast or in L-M or S-(L+M) chromatic contrast.

uncharacteristic of natural scenes, but are an inevitable consequence of natural variations in the properties of observers. The resulting sensitivity differences are obviously minor compared to the very large changes in the csf resulting from image blur, but they nevertheless suggest that there are different adaptation states associated with different refractive errors. (See also Mon-Williams et al.¹⁷) Blur reduces the effective contrast of patterns, but as a result may reduce the magnitude of adaptation to pattern contrast, which may offset (weakly) the losses in spatial sensitivity.

3.2. Color vs. luminance sensitivity

In the next set of measurements we compared the spatial adaptation effects for luminance vs. chromatic contrast. As noted in the introduction, the spectral slopes of natural images are roughly similar for luminance and chromatic spectra, while the csf's for luminance and color are markedly different. To examine whether the differences in the csf's might result in different patterns of adaptation, we repeated our previous measurements of threshold sensitivity, but with equiluminant stimuli. For these experiments the adapting stimuli were synthetic noise images filtered over a range of spectral slopes (Figure 6), rather than actual natural scenes as used in assessing refractive errors.

Figure 7 plots the chromatic csf before or after adaptation to the different image sets. The adapting and test stimuli were all defined by chromatic variations along the L-M axis. Each panel plots the after-effects measured for adapting images with a different α value. As we found previously for luminance contrast, adaptation to spectrally flat images had weak effect on

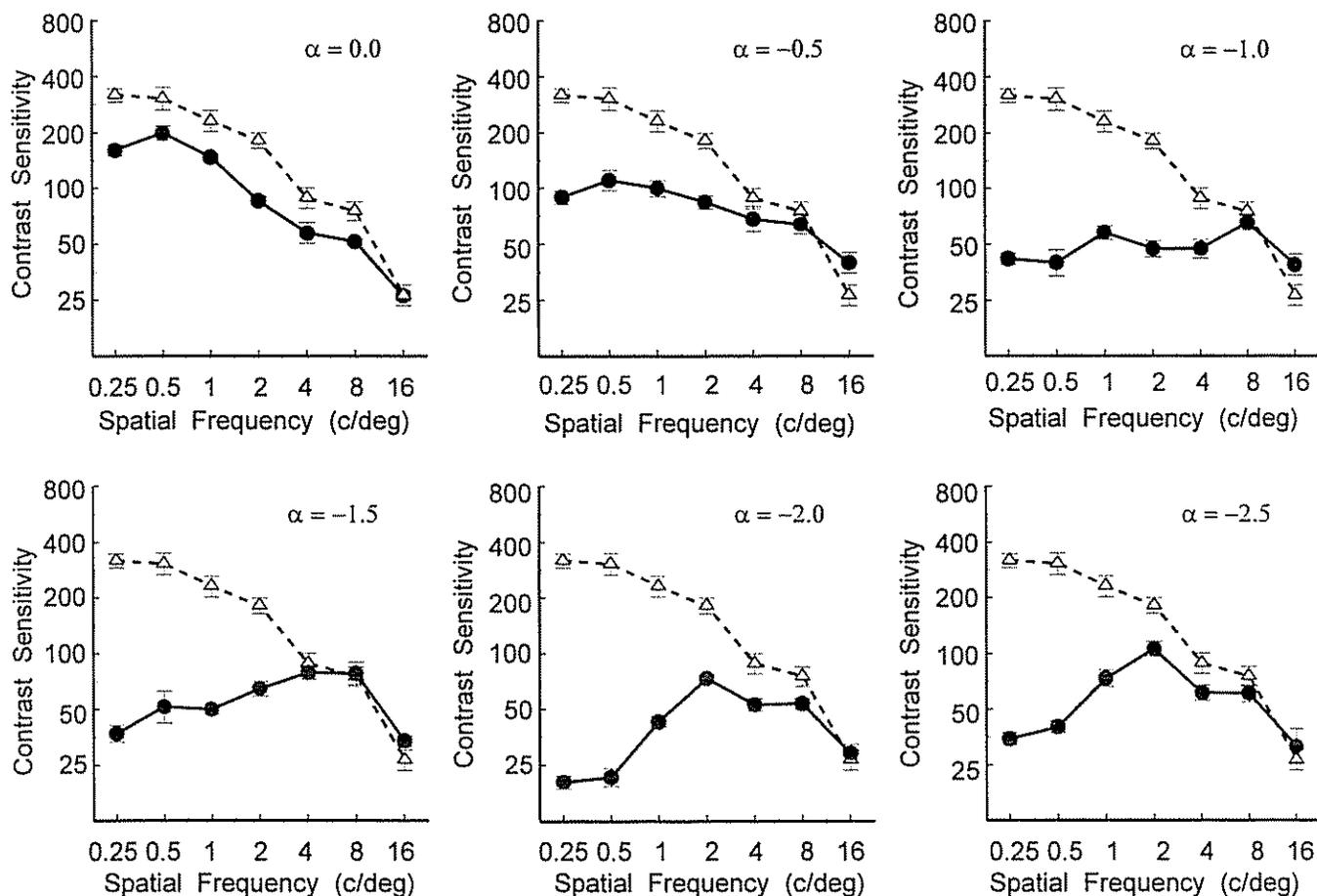


Figure 7. Chromatic (L-M) csf's measured before (triangles) or after (circles) adaptation to chromatic images. Each panel plots the adaptation effects for image sets with a different spectral slope. Observer MW.

the detection thresholds, while thresholds at low to medium spatial frequencies become progressively more elevated as the images become increasingly more biased toward low frequencies. In the case of chromatic contrast these threshold changes are very large, exceeding 1 log unit for some conditions. Moreover, they are clearly selective for lower frequencies, to the extent that following adaptation to the steeper spectra, the chromatic csf actually shifts from its characteristic lowpass shape to a bandpass shape more similar to the luminance csf.

These results are confirmed in Figure 8 for two further observers. In this case the adapting stimuli all had a fixed spectral slope of -1 , but were defined by luminance contrast (left column) or two different types of chromatic contrast, corresponding to variations along the L-M axis (center) or the S-(L+M) axis (right). Two features are again conspicuous in these results. First, the after-effects appear largely similar for the two different chromatic axes, but are substantially stronger than the after-effects for luminance adaptation. For example, observer JS in fact showed little adaptation to luminance contrast, yet large threshold changes for either chromatic direction. Second, the chromatic adaptation again has a large effect on the shape of the chromatic csf, so that after adaptation both chromatic csf's shift from clearly lowpass to weakly bandpass.

Figure 9 compares directly the sensitivity changes for chromatic and luminance adaptation. The chromatic after-effects appear much stronger and more selective for lower frequencies. This suggests that in natural viewing adaptation to chromatic contrast may strongly affect spatial chromatic sensitivity, and is consistent with the inherently greater sensitivity to low-frequency chromatic variations in the visual system. However, there are two complications in assessing these results. First, the scaling of luminance and chromatic contrast is arbitrary, and it is therefore difficult to compare directly the relative magnitude of the luminance and chromatic effects. (We are currently exploring how the spatial adaptation effects depend on the relative contrasts along different color directions for natural scenes.)

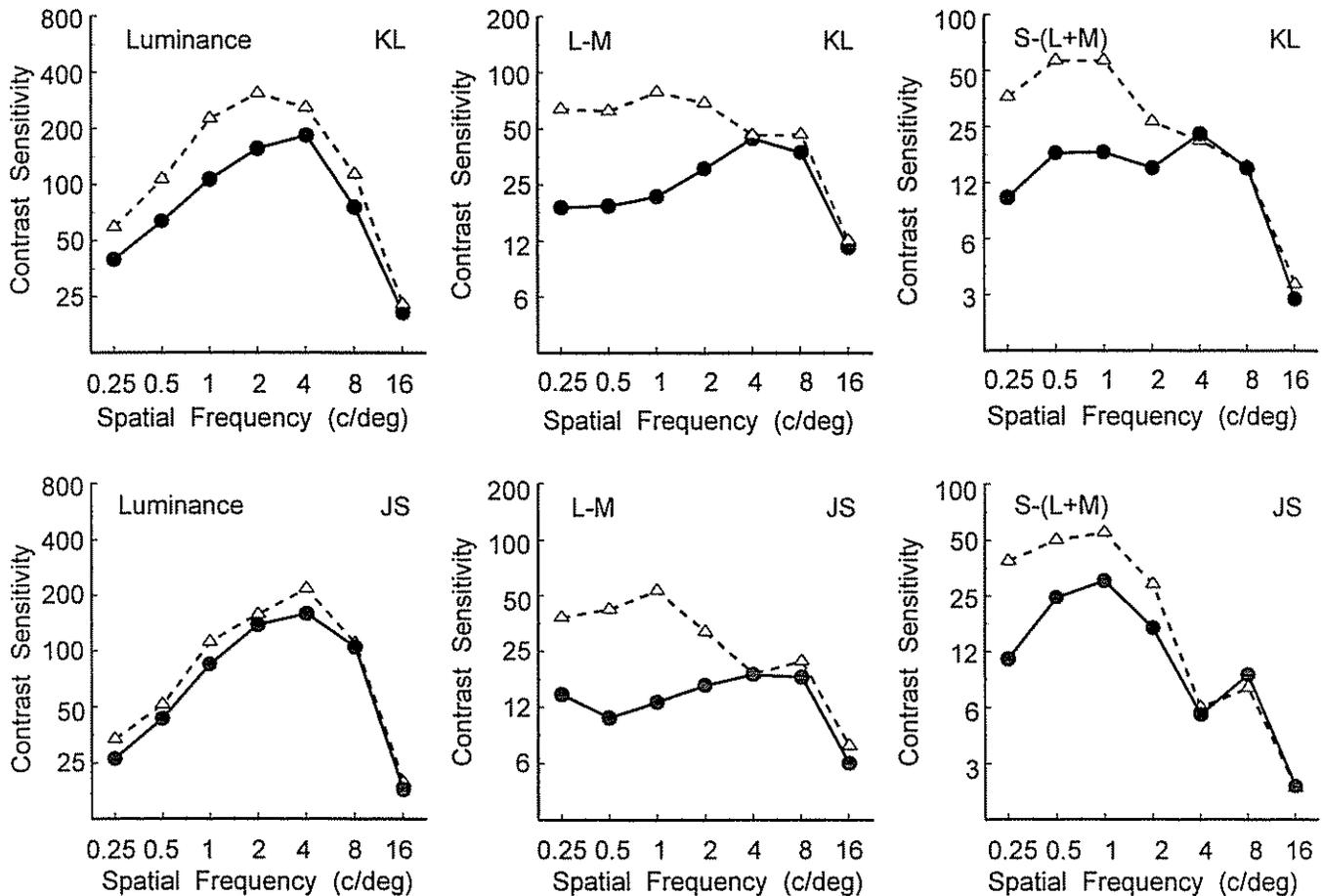


Figure 8. CSF's before (triangles) or after (circles) adaptation compared for luminance (left), L-M (middle) or S-(L+M) (right) contrast. The two rows plot results for observer KL (top) or JS (bottom).

Second, at higher frequencies the chromatic csf may in fact be limited by artifactual luminance contrast in the gratings, resulting from chromatic aberration¹⁸. We made no effort to correct this aberration because our interest was in assessing the adaptation effects for chromatic contrast in images, and not in isolating putative chromatic pathways in observers. However, because of this natural artifact, it is possible that the chromatic adaptation effects are much less selective for spatial frequency than Figure 9 suggests, and that the results instead partly depend on the progressive encroachment of luminance contrast in the test stimuli.

3.3. Spatial-frequency interactions in the adaptation effects

The preceding results confirm Webster and Miyahara³² in showing that adaptation to natural image spectra consistently affects spatial sensitivity by selectively elevating detection thresholds at low to medium spatial frequencies. In the final set of experiments we asked whether the low frequency bias in the adaptation resulted simply from a paucity of stimulus contrast at higher frequencies or because the adaptation effects across different frequencies are not independent. To examine this, we again measured the effects of adaptation to filtered noise images with $1/f$ spectra, but this time compared the after-effects at different frequencies when energy below a certain cut-off frequency was removed from the adapting images. Figure 10 shows examples of the resulting highpass-filtered images. The original $1/f$ image is shown in the top-right panel of Figure 6, while the images in Figure 10 were derived by filtering out frequencies below the specified cut-off. The csf's were then measured after adapting to image sets defined by different cut-offs.

In Figure 11 the threshold changes resulting from the adaptation are plotted for two observers. In this figure each panel shows the sensitivity change for a single spatial frequency, as a function of the cut-off frequency of the adapting set. Thus the

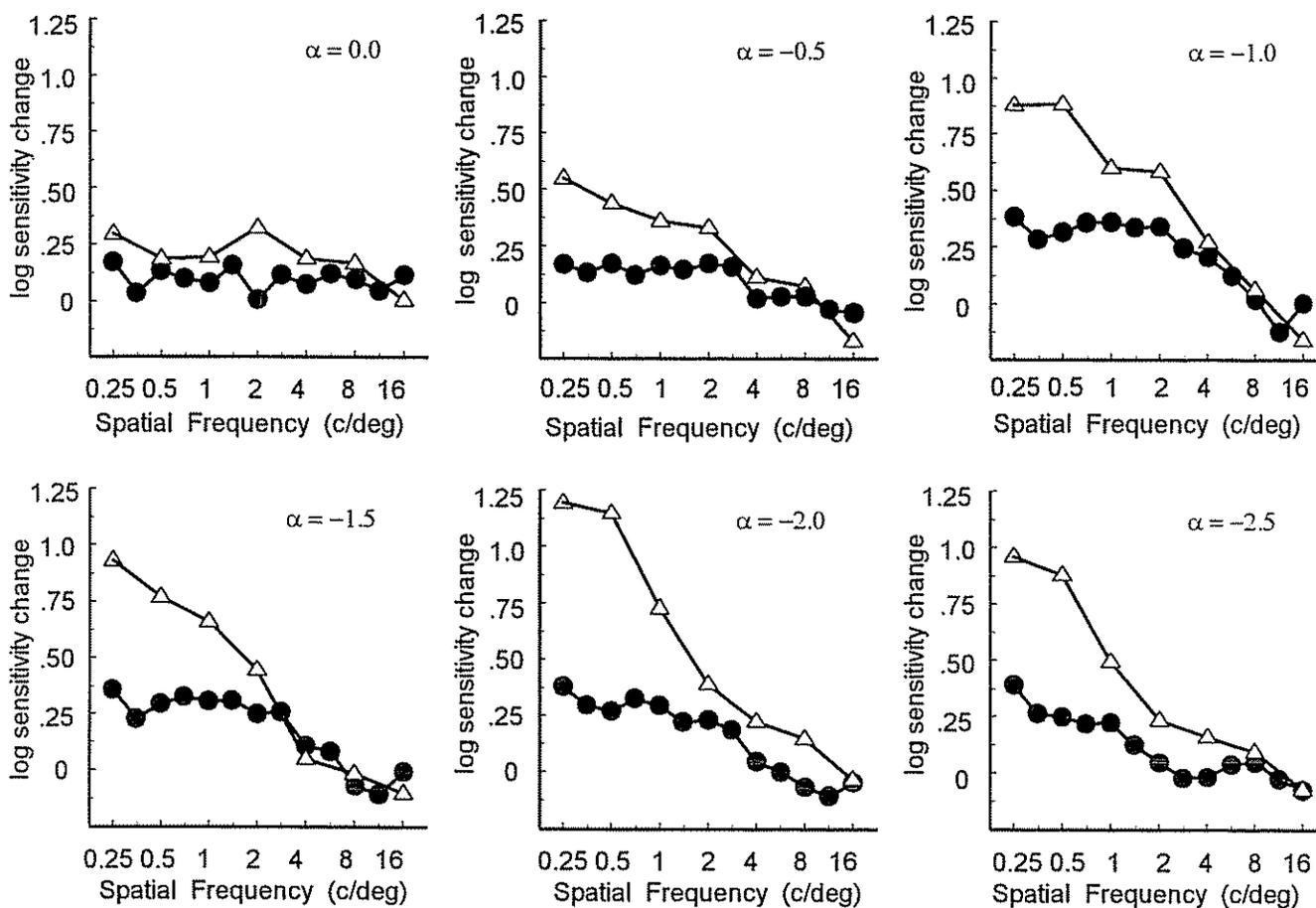


Figure 9. Comparison of adaptation effects for the L-M chromatic images (from Figure 7) and luminance images (from Webster and Miyahara³²). Plots show the log change in threshold sensitivity for the chromatic (triangles) or luminance (circles) measurements, with different panels plotting the results for adapting images with different spectral slopes.

individual curves do not show the effects of individual adapting sets as in previous figures, but instead show directly how adaptation at a single frequency depended on the frequency content of different adapting images. Reducing the cut-off frequency always added energy to the spectra, yet the largest adaptation effects consistently occurred when the test frequency was similar to the cut-off frequency. In particular, after-effects at the highest test frequencies (8 and 16 c/deg) are evident when the adapting images were confined to these frequencies, while generally absent when observers instead adapted to the broader-band images. (The results also show that the lack of adaptation observed at high frequencies for the broadband images cannot be due to a limited spatial resolution in the images.) The results are thus reminiscent of the interactions revealed in previous studies of the compound adaptation effects using simple grating pairs^{14, 15, 19, 25, 26}. This suggests that the pattern of spatial adaptation effects for natural images depends in part on highly nonlinear properties of spatial adaptation, and therefore cannot be predicted simply from the image spectra and how these might be weighted by frequency-selective filtering. Similarly, Barlow and Földiák^{2, 3} have shown that the selectivity of adaptation need not reflect the intrinsic tuning properties of the adapted mechanisms. (We are currently exploring whether there are spatial-frequency interactions for chromatic spatial patterns. It is interesting that a similar compound adaptation effect may not occur in measurements of color-selective adaptation. For example, Webster and Mollon³⁴ found that the magnitude of adaptation along one chromatic axis (e.g. L-M) was largely unaffected by adding uncorrelated modulations along the orthogonal axis [e.g. S-(L+M)]. However, this stimulus arrangement may be more analogous to decorrelating the different grating components (e.g. by moving them separately), a manipulation that restores the adaptive influence of the higher harmonic¹⁵.)

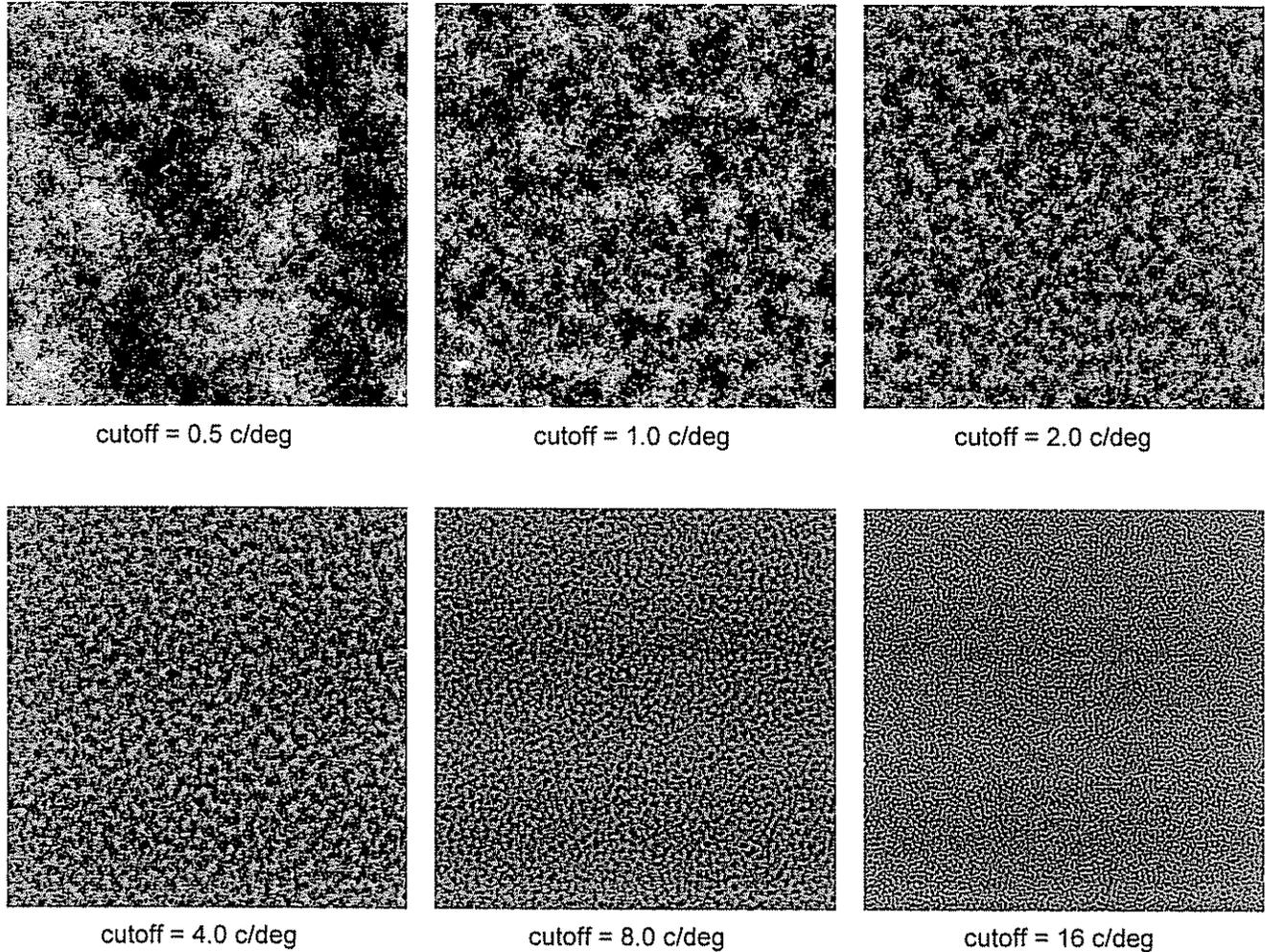


Figure 10. Examples of the filtered noise images used for assessing frequency interactions in the adaptation effects. All images had a spectral slope of -1 but were filtered to remove frequencies below cut-off frequencies ranging from 0.5 to 16 c/deg.

4. CONCLUSIONS

The present results add to our previous reports^{31, 32, 34, 36} in showing clear sensitivity changes induced by adaptation to the spatial and chromatic structure of natural images. Pattern adaptation has been viewed as a maladaptive response (e.g. fatigue) to unnatural viewing conditions (e.g. persistent fixation of patterns), and thus as irrelevant to natural vision. However, we argue that such adaptation effects are an intrinsic feature of the visual response to any stimulus, and are thus a necessary consequence of the act of seeing. Natural images share a common spatial structure, and in this regard may present the visual system with persistent patterns of stimulation. Adaptation to these patterns significantly shapes visual sensitivity, and thus defines the sensitivities most relevant for characterizing normal vision. Our present results suggest that adaptation to the common spatial statistics of images is fairly stable under moderate changes in the image spectra, owing to differences in the images themselves (changes in the spectral slope) or to changes in the observer (defocus). However, large changes in the spectra do alter the tuning of the sensitivity changes, and while such steep spectra may not occur in natural scenes, they may not be uncommon in the retinal image if the image is often out of focus. Our results also show strong changes in chromatic sensitivity induced by adaptation to chromatic contrast in images, and this may differ from the tuning for luminance contrast in ways that are consistent with the different filtering properties of the visual system for luminance and chromatic contrast. However, in our final set of results we have shown that the adaptation effects at different spatial scales are not independent. Thus, while the adaptation effects are important in describing the operating states induced by natural viewing, they may not be predictable from linear filtering characteristics of the visual system.

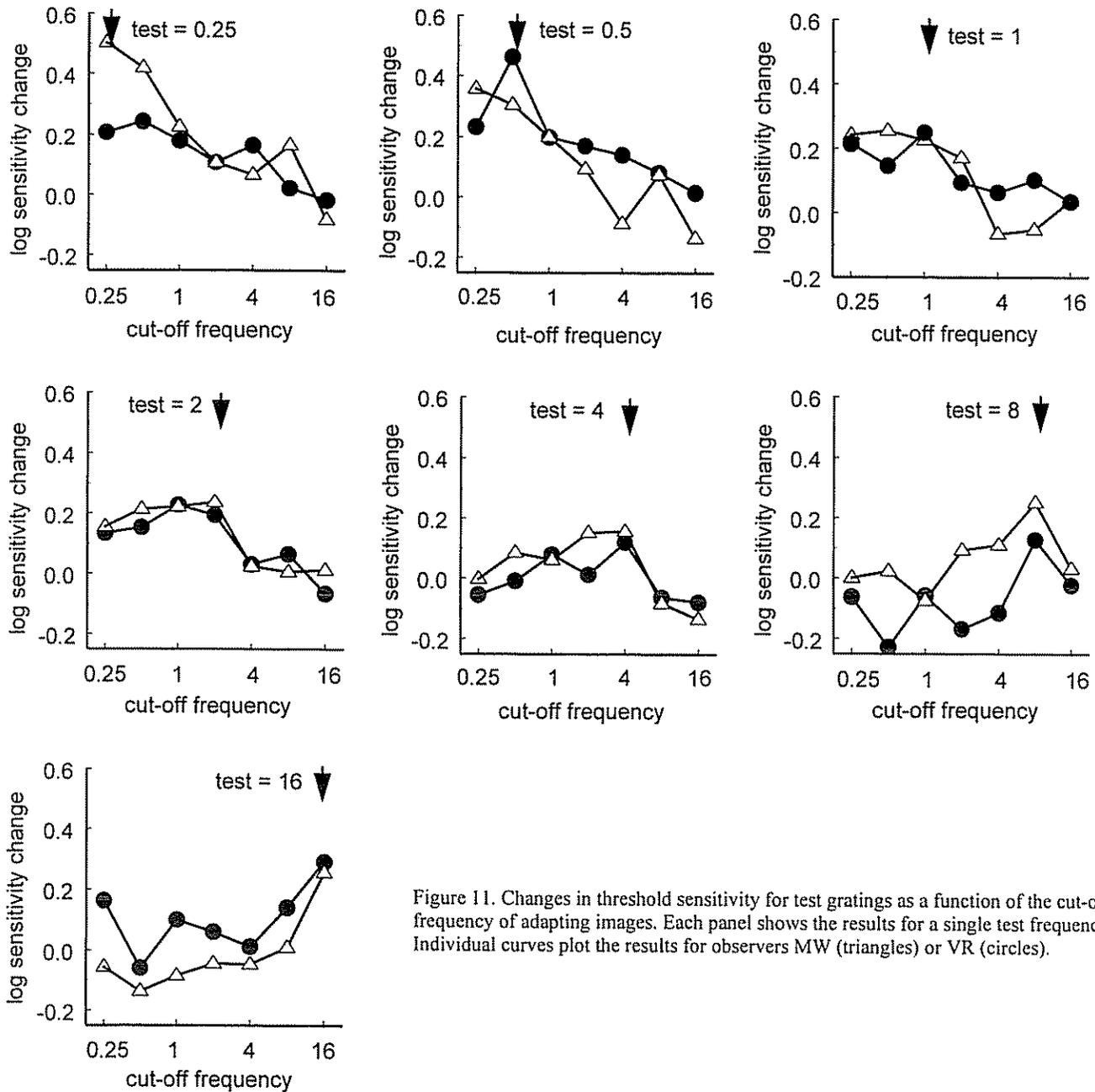


Figure 11. Changes in threshold sensitivity for test gratings as a function of the cut-off frequency of adapting images. Each panel shows the results for a single test frequency. Individual curves plot the results for observers MW (triangles) or VR (circles).

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