Visual adjustments to temporal blur

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After observers have adapted to an edge that is spatially blurred or sharpened, a focused edge appears too sharp or blurred, respectively. These adjustments to blur may play an important role in calibrating spatial sensitivity. We examined whether similar adjustments influence the perception of temporal edges, by measuring the appearance of a step change in the luminance of a uniform field after adapting to blurred or sharpened transitions. Stimuli were square-wave alternations (at 1 to 8 Hz) filtered by changing the slope of the amplitude spectrum. A two-alternative-forced-choice task was used to adjust the slope until it appeared as a step change, or until it matched the perceived transitions in a reference stimulus. Observers could accurately set the waveform to a square wave, but only at the slower alternation rates. However, these settings were strongly biased by prior adaptation to filtered stimuli, or when the stimuli were viewed within temporally filtered surrounds. Control experiments suggest that the latter induction effects result directly from the temporal blur and are not simply a consequence of brightness induction in the fields. These results suggest that adaptation and induction adjust visual coding so that images are focused not only in space but also in time. © 2005 Optical Society of America

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1. INTRODUCTION

Processes of adaptation are important for calibrating visual coding in order to match the sensitivity of the visual system to the characteristics of the visual environment.[1,2] For example, chromatic adaptation tends to rebalance the sensitivity to color so that the average chromaticity in the scene is perceived as gray. Such adjustments increase coding efficiency by centering the response range around the mean stimulus level, and by equating the response levels across visual mechanisms. They also contribute to perceptual constancy by discounting both variations in the environment, such as changes in scene illumination,[3] and variations in the observer, such as changes in spectral sensitivity with aging.[4]

Recently, Webster *et al.*[5] examined the role of adaptation in calibrating spatial sensitivity, by examining how the visual system adjusts to changes in image blur. Subjects adapted to images that were blurred or sharpened by filtering the image amplitude spectrum, and then adjusted the amplitude spectrum of a test image until it appeared properly focused. After viewing a blurred stimulus, a physically focused image appeared too sharp, and thus the image that appeared best focused was moderately blurred. When subjects instead adapted to a sharpened image, the opposite aftereffects were observed. Similar changes in perceived focus were also found when test stimuli were presented within a blurred or sharpened surround. That is, a central image appeared sharper (or blurrier) when the surrounding images were blurred (or sharpened). These adaptation and induction effects suggest that the visual system can rapidly adjust to changes in the spatial statistics of the retinal image, an adjustment that may be crucial for maintaining the match between spatial sensitivity and the spatial structure of images.[6] In particular, adaptation could serve to balance the activity across the set of spatially selective mecha-

nisms encoding different spatial scales or edge profiles in the image. In turn, this could play a central role in maintaining perceptual constancy for image focus despite changes in the scene (e.g., conditions of poor visibility) or the observer (e.g., because of optical errors). For example, such adaptation could selectively compensate for the aberrations specific to an individual's eyes.[7]

In the present study, we asked whether similar adaptive adjustments to those regulating spatial coding might also regulate the encoding of temporal information in the visual system. Like the variations over space, the variations over time in natural scenes have a characteristic form with power decreasing as temporal frequency increases,[8,9] and encoded by mechanisms responsive to different temporal scales.[10] Adaptation might therefore again be important for calibrating the sensitivity of these mechanisms. To test this, we measured the perception of blur in time, and how the perceived focus of a transition over time was affected by adaptation to temporally blurred or sharpened transitions or by induction from blurred or sharpened temporal changes in the surround. Our results suggest that the visual system adjusts in very similar ways to spatial and temporal blur, suggesting that visual coding may be calibrated in functionally similar ways for edges in both space and time.

2. METHODS

Stimuli were presented on a SONY Multiscan 500 PS monitor driven at a noninterlaced frame rate of 160 Hz and controlled by a Cambridge Research System VSG 2/5 graphics card. Phosphor luminance was calibrated with a PR650 spectroradiometer and linearized through lookup tables. Subjects viewed the display binocularly from a distance of 1.75 m in an otherwise dark room, and made responses with a handheld keypad. The three authors served as observers.

Except where noted, test stimuli were uniform 4 deg fields, presented on a 13×10 deg background with the same mean luminance (40 cd/m²) and chromaticity (CIE 1931 $x,y = 0.289, 0.299$). The luminance of the test field was varied in a square wave that was filtered by adjusting the slope of the amplitude spectrum in order to temporally blur or sharpen the transitions. For an unfiltered square wave, the spectrum of log-amplitude versus log-frequency has a slope of -1. Steeper slopes (<-1) reduced the relative amplitude of higher temporal frequencies and thus blurred the edge, while shallower slopes (>-1) gave more weight to higher frequencies and thus sharpened the transition. Figure 1 shows examples of the waveforms for blurred, focused, or sharpened temporal edges. In the experiments, the slope was varied in small increments to provide a finely graded series of stimuli that varied between slopes of -1.5 (moderately blurred) and -0.5 (moderately sharpened). On each frame the intensity of the waveform was computed by summing the harmonics of a square wave, with the relative amplitude of the frequency components scaled by f^s, where s was the slope of the spectrum on log–log axes. Contrast was renormalized so that all stimuli had the same rms contrast of 0.3 after filtering.

On each trial the test flicker was shown for a fixed interval, and subjects made a two-alternative-forced-choice response to indicate whether the temporal change appeared "too blurred" or "too sharp." In some cases this judgment was made without a comparison stimulus (by simply judging whether the flicker appeared sharpened or blurred). In most cases subjects instead compared the test to a reference field that was shown simultaneously with the test. The blur level of subsequent stimuli was varied using two randomly interleaved staircases that changed the slope in steps of 0.02 depending on the sign of the observer's response. Measurements continued until both staircases had reversed 8 times, with settings calculated from the mean of the last six reversals for each staircase. Results reported are based on the average of six settings for each condition, with error bars representing ±1 standard deviation.

Measurements of perceived focus were made under three conditions. In the first, subjects viewed a single centrally fixated field and adjusted the slope until the stimulus appeared to change in square wave steps. These measurements were used to assess how well observers could judge temporal blur or sharpening in the flickering stimuli. In the second condition, the settings were repeated after adapting to blurred (slope=-1.5) or sharpened (slope=-0.5) variations in the field. Stimuli with these slopes were chosen because they appeared clearly blurred or sharpened (at lower alternation rates), and remained within a range at which the waveform could be displayed without significant truncation of the luminance spikes for the sharpened edges. Subjects initially adapted for 120 s. Test stimuli were then shown for 1 s alternated with 5 s intervals of readaptation. The test and adapt intervals were separated by gaps of 0.25 s, during which the field was shown at the mean luminance. To heighten sensitivity to changes in the appearance of the test with adaptation, for these measurements we presented two fields centered 2.5 deg to either side of a central fixation point. In one field the adapting stimulus was blurred in time, while in the other it was sharpened. The test stimuli were then adjusted until the two tests appeared the same. The test slopes were yoked and pivoted around the focused slope of -1, so that increasing the slope of one resulted in a corresponding decrease in the slope of the other. This relative measure provided a sensitive index of adaptation differences between the two fields and was easier to judge than the absolute focus of the stimulus, especially at higher alternation rates. However, it has the disadvantage that the measures do not indicate the actual shifts in perceived blur induced by the individual adapting fields. Finally, in the third condition we measured the effects on perceived temporal blur of temporal variations in the spatial surround. In this case the test stimuli were reduced to 2 deg fields, centered within a 6 deg uniform surround. As with the adaptation, for these induction experiments we presented two fields on each side of fixation, with a blurred temporal variation in one and a sharpened variation in the other, and subjects adjusted the slopes of the
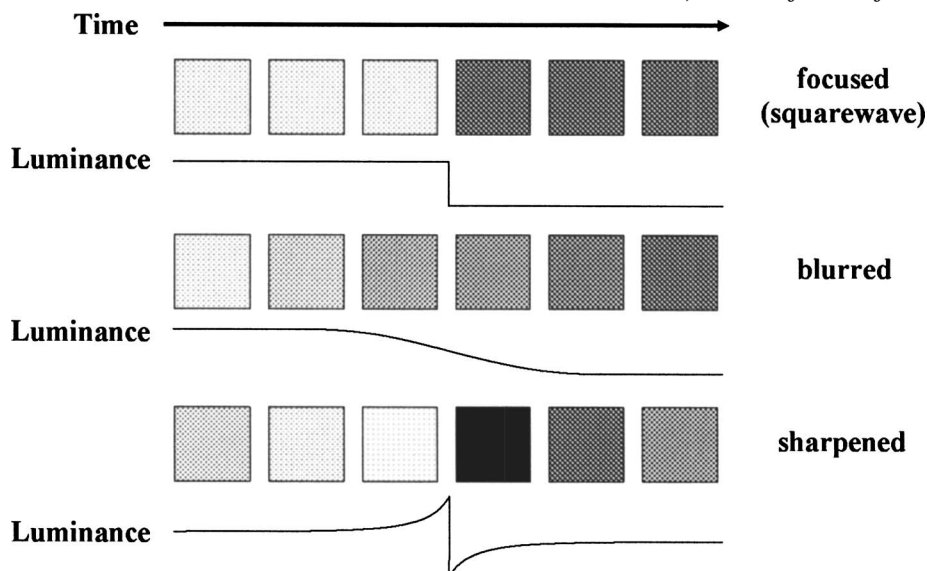

Fig. 1.   Examples of the luminance profiles for a temporally focused, blurred, or sharpened step change.
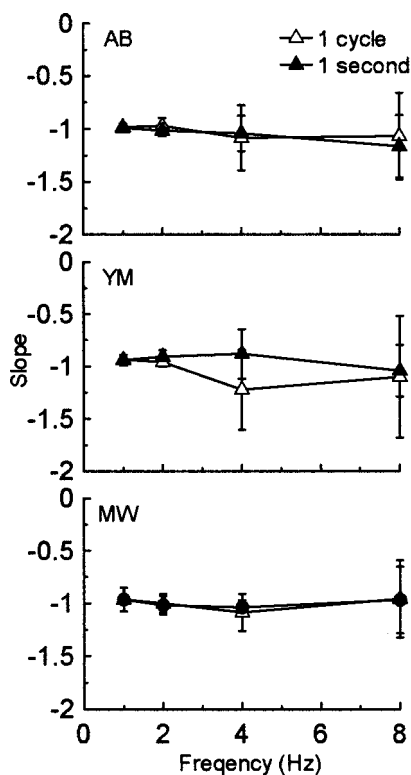
Fig. 2.   Stimulus slopes perceived as a square wave alternation in the flicker. Each panel plots the results for an individual observer. Points show the mean setting ±1 standard deviation. Open triangles: settings for a 1 cycle alternation in the field (presented in temporal sine phase). Solid triangles: results for a 1 s presentation at each frequency.

central tests until they appeared the same. Stimuli in this case were presented for 1 s on each trial, with the fields shown at the mean luminance between each presentation.

3. RESULTS

A. Sensitivity to Temporal Blur
Observers are highly sensitive to blur in spatial patterns,[11–14] and can adjust the amplitude spectra of images to come close to recovering the original slopes of physically focused images.[15,16] In the first experiment we asked whether subjects are similarly sensitive to changes in the waveform of temporal variations. In this case the task was simply to set the spectral slope until the test field appeared to vary as a square wave. The settings were made for fields alternating at rates of from 1 to 8 Hz, and displayed for a fixed interval of 1 s or for a single cycle of the alternation in sine phase.

Figure 2 plots the results for the three observers. All three subjects showed good sensitivity to temporal focus at 1 or 2 Hz. That is, all three were consistently able to set the slope of the amplitude spectrum so that field luminance varied as a focused square wave transition (slope=−1). However, the variance in repeated settings increased substantially at the higher frequencies. Thus at high alternation rates the ability to judge the blur or sharpness of the individual transitions was poor. This pattern was very similar whether the test duration was 1 cycle or 1 s, and thus is unlikely to reflect "crowding"

from multiple cycles at the higher frequencies. Instead, it may suggest that absolute judgments of temporal blur depend on comparisons that extend to lower frequencies or longer time intervals than are available in the 4 or 8 Hz stimuli, perhaps because the temporal modulation transfer function of the visual system limits the sensitivity to the higher harmonics at the higher flicker rates.

B. Adaptation to Temporal Blur
Adaptation to a blurred or sharpened edge in space can strongly affect the perceived blur of subsequently viewed spatial edges.[5] In the next experiment we tested whether this adaptation affects temporal edges as well as spatial edges. As noted, we tested this by matching the perceived focus of temporal changes in two fields that were presented after adaptation to temporally blurred or sharpened changes within each field. Aftereffects were assessed for test alternation rates of 1, 2, or 4 Hz. The adapting flicker alternated at the same rate as the tests, and was temporally blurred (−1.5) in one field while sharpened (−0.5) in the other. Settings were repeated with the blurred adaptor on each side.

Figure 3 shows the magnitude of the aftereffects for each observer. Open symbols correspond to the case in which the sharpened adapting transition was shown above fixation and the blurred transition was shown below, and plot the difference in the top minus the bottom field. The positive sign of the match indicates that adaptation caused temporal edges in the upper field to appear
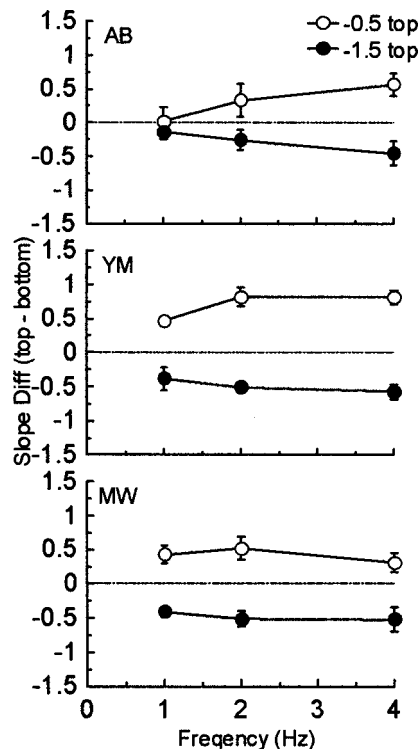

Fig. 3.   Effects of adaptation on the perceived temporal edges. Points plot the physical slope differences between two tests that appeared matched, one in a field following adaptation to temporally sharpened steps (slope=−0.5) and the other following temporally blurred steps (slope=−1.5). Open symbols: sharpened adaptation in the top field. Solid symbols: blurred adaptation at top.
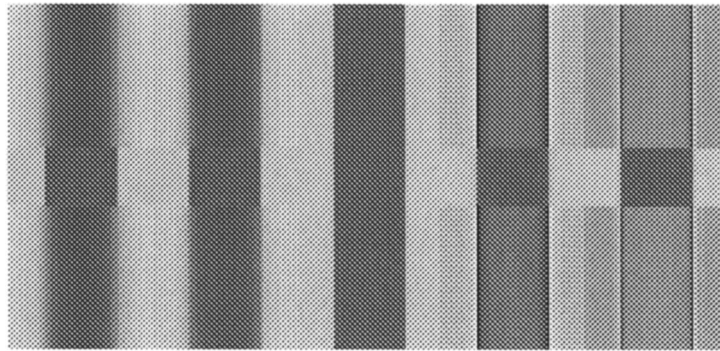
Fig. 4. Induction in spatial edges. The center row of bars is a square wave. However, the center bars at left appear sharpened because they abut blurred bars, while the center bars at right appear blurred because the surrounding bars are physically sharpened.

more blurred than the lower field, so that subjects had to physically sharpen the upper test (while physically blurring the lower test) in order to achieve the match. This is consistent with each adapting field inducing an aftereffect of opposite sign in the test edge. That is, blurred fields caused the test to appear sharper and vice versa. The solid symbols show the results for the mirror stimulus conditions and replicate the aftereffects.

Again, the points in Fig. 3 plot the difference in spectral slope between the two test fields, and thus should be roughly double the slope change induced in either individual field (if the aftereffects for blurred and sharpened stimuli are symmetrical). The relative matches occurred for test slope differences approaching or exceeding 0.5 for many of the conditions, and thus are 50% or more of the slope difference between the two adapting levels. This suggests that the aftereffects on perceived temporal blur are large, and consistent with this, the phenomenal changes in the test fields were often obvious. For example, after adapting to a blurred alternation, the square wave transitions appeared to have salient flashes or temporal transients that closely resembled the appearance of physically sharpened changes. The strong aftereffects for temporal blur, at least under optimal temporal conditions, thus appear on par with the salience of the aftereffects observed for spatial blur.

Notably, the relative matching task revealed large adaptive shifts at 4 Hz, even though subjects were relatively bad at judging absolute blur at this test frequency. In fact, for observers AB and YM, the aftereffects were stronger at 4 Hz than at 1 Hz and thus showed a significant effect of frequency, as confirmed by ANOVA's showing a main effect of frequency [$F(2,35) = 19.3$, $p < 0.0001$ for AB; $F(2,35) = 22.9$, $p < 0.0001$ for YM]. In informal pilot settings we also noticed that the aftereffects tended to be weak for very slow alternation rates. Threshold elevations and changes in apparent contrast following flicker adaptation also tend to be weaker at low frequencies.[17–19] This could be because these slow rates provide a lower rate of stimulation and thus are less potent as adapting stimuli, but might also reflect differences in the adaptability of channels tuned to different temporal frequency ranges. For example, Solomon *et al.*[20] recently found that geniculate M cells (and their retinal inputs) are strongly adapted by high temporal frequency stimulation, while P cells show little adaptation.

C. Spatial Induction of Temporal Blur
In the final set of experiments we examined whether blurring in time can be influenced by temporal blur in surrounding spatial regions. As noted, the perceived spatial blur of a pattern can be strongly biased by blurring or sharpening the surround.[5] For example, Fig. 4 shows a central row of square wave edges that are juxtaposed between surrounding edges that vary from blurred to sharpened (from Ref. 5). The edges abutting the blurred transitions are visibly sharpened, while the sharpened surround causes the central bars to appear more blurred. We again tested whether analogous temporal induction effects might bias the perceived focus of edges in time.

Observers matched the test waveforms presented in 2 deg test fields centered in 6 deg surround fields. The surrounds varied in phase with the test but with either blurred or sharpened transitions. The matches are plotted in Fig. 5. As before, the two curves in each figure are for mirror stimulus conditions and again are consistent with a large induction effect from the surrounds over the range of frequencies tested. Thus blurred surround transitions caused the temporal transitions in the central patch to appear sharper, while sharpened surrounds caused the center changes to appear more gradual. Moreover, these changes were again perceptually clear, in the same way that the spatial effects are clear when inspecting Fig. 4.

D. Controls for Light Adaptation and Induction
Both the adaptation and induction effects could arise if the visual system calibrates temporal coding in order to adjust to changes in the stimulus across both time and space. However, an alternative possibility is that the perceived changes are a consequence of simple light adaptation and brightness induction from the surrounds. It is therefore important to consider whether such processes provide a plausible basis for the blur effects. In the case of adaptation, changes in light adaptation are unlikely to play a role in the temporal blur settings, since the fields are spatially uniform and have the same time averaged luminance, and were varied at temporal frequencies that maintain a steady state of light adaptation.[19] Similarly, light adaptation alone cannot account for the blur aftereffects in spatial patterns, since the aftereffects transfer across different spatial patterns and remain strong when the images are spatially jittered during the adaptation,[5]
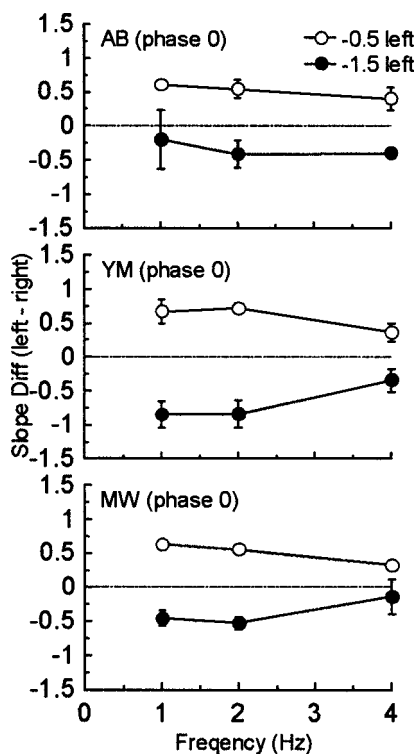
Fig. 5. Effects of induction on perceived temporal edges. Points plot the slope differences between two tests that appeared matched, one surrounded by a field with sharpened flicker (slope=−0.5) and the other in a surround with blurred flicker (slope=−1.5). Open symbols: sharp surround flicker on left. Solid symbols: blurred surround flicker on left.

conditions that are routinely used to minimize local differences in light adaptation.[1]

In the spatial blur induction effects, simple brightness differences in the surrounds cannot explain the changes in perceived focus, since they persist for complex images and thus do not depend on the precise alignment of edges.[5] However, the case for temporal blur induction is not as clear. The stimuli we used are very similar to ones that De Valois *et al.*[21] used to examine the temporal limits of brightness and color induction. They showed that sinusoidally varying surrounds induced changes in the brightness or color of a blank test field that were roughly sinusoidal and out of phase with the surround, and that strong induction occurred for temporal frequencies of 2 Hz or less. Thus our stimuli—at least at the lower temporal frequencies—should have included strong brightness changes from the surrounds. Suppose that these induced brightness changes followed the changes in the surround. Temporally blurred surrounds would then induce an out-of-phase blurred modulation in the center field. Superimposing this modulation on a square wave alternation would tend to cancel the lower temporal frequencies and thus might exaggerate the higher frequencies, so that the resulting stimulus would appear sharpened. Conversely, if temporally sharpened surrounds were capable of inducing a sharpened out-of-phase brightness modulation, then a superimposed square wave alternation might appear blurred. Accordingly, we made a number of control settings to test whether the temporal

blur induction might be merely a trivial consequence of the induced brightness changes.

In the first control condition, we repeated the blur matches but with the test and surround fields modulated 180 deg out of phase. Shifting the surround phase should lead to opposite blur effects if the perceived blur depended simply on summing the induced and physical brightness changes, since these would now be in phase in the test field. However, the effects instead tended to be weaker and not consistently in the opposite direction of the in-phase surrounds. The blur was also more difficult to judge in these conditions, and settings were much more variable across subjects (Fig. 6).

In the second control, we repeated the temporal blur induction but used checkerboard patterns for either the center or the surround, with individual checks subtending 0.33 deg. In this case weaker brightness induction should occur for the checkered surround, since the local elements are varying out of phase and thus any induced brightness changes should tend to cancel.[22] However, changes in perceived temporal blur were again found in the uniform test fields (Fig. 7).

Finally, we also attempted to measure directly the appearance of the brightness changes induced in a static field by the blurred or sharpened flicker in the surround. To do this, we modified the display so that on one side subjects were shown only the surround modulation (with no physical modulation in the center). The induced brightness changes in the center were matched by adjusting the slope of a physically varying comparison field presented on the other side (with a static surround). Surprisingly, in this case the matches showed very little
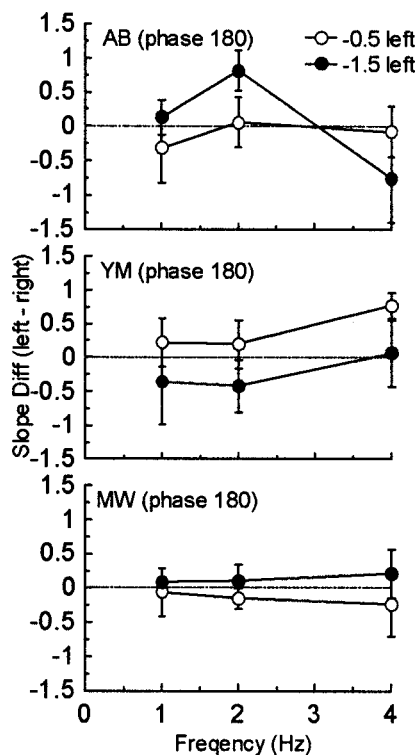

Fig. 6. Difference in matching slopes when the two surround modulations were varied 180 deg out of phase with the center modulation.
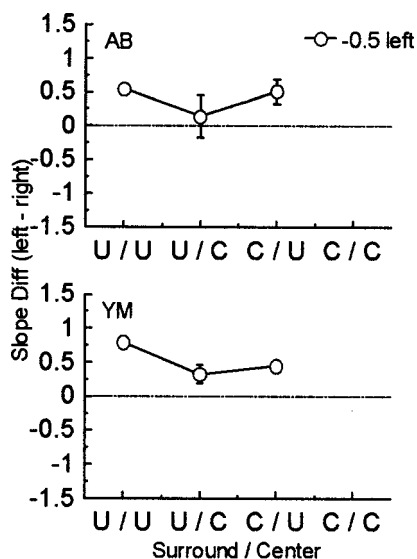
Fig. 7.   Temporal blur matches when the center or surround was either a uniform field or checkerboard pattern. U/U: uniform surround and center. U/C: uniform surround and checkerboard center. C/U: checkerboard surround and uniform center.
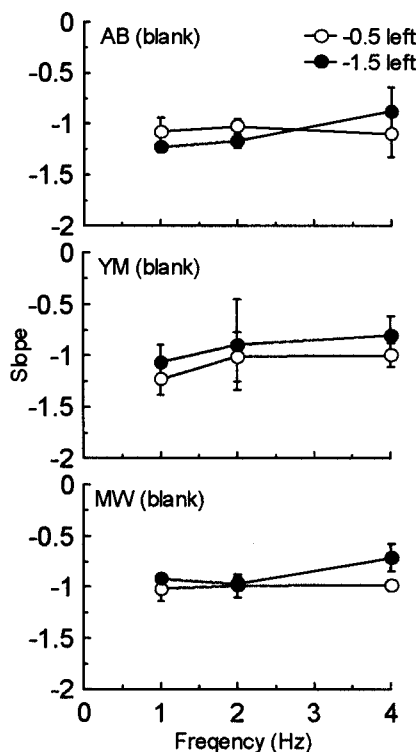

Fig. 8.   Matches to the brightness variations induced by blurred (solid circle) or sharpened (open circle) variations in the surround.

dependence on the surround slope. In particular, for both blurred and sharpened surrounds, the induced brightness changes were matched by physical variations with slopes close to −1, and thus appeared as simple step changes (Fig. 8). Thus the brightness induction from temporally blurred or sharpened variations did not itself appear correspondingly blurred or sharpened. Taken together, these controls suggest that like their spatial counterpart, the temporal blur induction effects appear directly to reflect

changes in the temporal characteristics of the patterns, rather than arising as an indirect consequence of classic brightness induction.

4. DISCUSSION

To summarize, our results show that observers have good sensitivity to "focused" edges in time, at least at slower presentation rates, and that the perception of temporal focus can be strongly biased both by prior adaptation or simultaneous induction from temporally blurred or sharpened contexts. These effects for temporal blur thus mirror the visual adjustments to spatial blur. In some sense this similarity is surprising, for early channels mediating temporal coding are thought to be much coarser than spatial channels. For example, while the channels for spatial frequency are generally thought to have strong selectivity and form a dense distribution,[23] studies of temporal-frequency selectivity have typically found evidence for only two or three broadly tuned mechanisms,[24–28] and this bimodality is also observed in the temporal properties of geniculate and cortical cells.[29] Moreover, perceptual aftereffects from adaptation to sinusoidal flicker tend to show much less frequency selectivity than is typically found for spatial gratings.[18,30–32] For instance, adapting to a spatial grating strongly biases the perceived frequency of subsequently viewed gratings,[33] but comparable robust aftereffects for temporal flicker are lacking.

On the other hand, it is not surprising that the visual system selectively adjusts to the temporal properties of stimuli. An obvious example of this is the very extensive literature on motion aftereffects and induced motion.[34] Temporal aftereffects have also been previously reported for spatially uniform fields that vary in luminance over time, similar to the type of stimulus we examined. Thus sawtooth variations in luminance have been found to produce polarity-selective changes in luminance detection thresholds,[35] and can produce suprathreshold aftereffects in the perceived dimming or brightening of fields (so that after viewing a field that is gradually brightened, a static field appears to be gradually dimming).[36] Moreover, like temporal blur, these sawtooth waveforms can influence appearance through both adaptation and induction.[37,38]

In the present study, we examined stimuli whose luminance variations were blurred or sharpened in time, to test whether the visual system might calibrate temporal sensitivity in ways that are functionally similar to the adaptive adjustments found previously for spatial sensitivity. Focused images may hold a special place in spatial vision, in the same way that achromatic stimuli are special in color vision. Natural images have a characteristic amplitude spectrum, in which amplitude varies inversely with spatial frequency (or as $1/f$, the spectrum that also characterizes a focused edge).[39,40] A number of studies have suggested that visual coding may be closely matched to this property. For example, the spatial statistics of images can be used to predict closely the spatial contrast sensitivity function and receptive field properties of retinal and cortical cells.[40–43] In visual cortex, cells vary in their preferred spatial frequency, and the bandwidth of the frequency tuning increases with peak frequency.[44] As

a result, sensitivity increases with increasing frequency, in a way that can compensate for the $1/f$ falloff in natural image spectra.[40] This predicts that the average responses of cells to natural images should be independent of spatial scale. In fact, equal response amplitudes at different scales might form a neural signature of physically focused images, just as equating chromatic responses might form the basis for perceiving "white." In turn, just as chromatic adaptation adjusts to biases in the light spectrum, adaptation to biased amplitude spectra could allow the visual system to track changes in image focus and thus maintain constancy for spatial focus (though the extent to which blur adaptation can be characterized as a simple renormalization of perceived focus remains uncertain).

Analogous arguments suggest that adaptation could play a similar role in the temporal domain. Like spatial variations, temporal variations in natural images are strongly correlated, such that the amplitude spectrum of the temporal variations falls with increasing temporal frequency.[8,9] Decorrelation and sparse coding of these variations can again predict the temporal tuning of the visual system and of neural receptive fields, and in particular predicts the bandpass temporal tuning of contrast sensitivity and neural responses.[43,45,46] Thus equating sensitivity at different temporal scales may again form the expected neutral point for visual coding and could be adjusted and maintained in similar ways by adaptation (though as noted above, the temporal sensitivity of the visual system appears to depend on coarser channels than those mediating spatial contrast sensitivity). This raises the question of whether "edges" are as important in the temporal domain as the spatial domain, for objects rarely appear or disappear. However, for moving objects (or, more important, moving observers[43]) in a three-dimensional world, such temporal edges do frequently occur as a result of occlusion and from changes in fixation.

We have discussed the adjustments to temporal blur as if they are driven simply by the stimulus amplitude spectrum. However, in the case of spatial blur there is evidence against this. Focused images can vary in their spectral slope, because the slope depends on both the amplitude of contrast and the density of structure at different scales.[15] Webster *et al.*[5] found that how adaptation in one image affected the perceived blur of another depended on whether the adapting image itself was focused and not simply on the average spectrum. Thus the aftereffects do not depend on independent adaptation to the average contrast at different scales. Recently, we have also found that adaptation to spatial blur in edge stimuli shows a strong dependence on the phase spectrum.[47] Specifically, the adaptation is substantially stronger for square wave edges than when the same frequency components are phase shifted to form triangular waves. We have not tested for comparable phase effects for temporal blur, but it may be that some aspects of the adaptation reflect adjustments that are specialized for asymmetric edge profiles. Such results highlight the fact that the actual stimulus features controlling blur adaptation—and indeed controlling the perception of blur—remain poorly understood. However, whatever their basis, these adjustments appear to operate in functionally similar ways in both space and time.

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