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Short Communication

Motion Sharpening: Evidence for the Addition of High Spatial Frequencies to the Effective Neural Image

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The perceived blur of drifting sinusoidal gratings was compared to that of static, blurred "square wave" gratings before and after adaptation to a missing fundamental (MF) pattern. The results indicate that the perceived blur of a drifting sine grating is inversely related to its drift speed. However, after adaptation to a MF pattern, this effect is reduced. The adaptation effect is most profound for low contrast gratings. The results provide tentative evidence for a non-linear stage in motion processing which serves to introduce higher frequencies into the neural image which are not present in the original signal. Copyright © 1996 Elsevier Science Ltd.

Motion perception   Sharpening   Blur

INTRODUCTION

Ramachandran *et al.* (1974) reported that drifting blurred images may appear sharper than when they are static. They used a sequence of images, each individual frame of which was blurred, to produce an apparent motion stimulus. Their subjects reported that the motion stimulus appeared to be in clear focus but the individual static frames appeared blurred. Upon the basis of this finding they suggested that the visual system incorporates a motion deblurring mechanism. More recently, Bex *et al.* (1995) have confirmed and extended their finding. They found that the perceived blur of drifting sinusoidal patterns and blurred edges was inversely related to drift speed.

Ramachandran *et al.* (1974) suggested two possible explanations of motion sharpening. The first, which they termed "sharpness constancy", invoked the notion that "*. . . the brain takes into account the fact that the object is moving and attributes the absence of sharpness entirely to the movement*". Similarly, Bex *et al.* (1995) suggested that a default condition may be to assume that all edges are sharp and hence an object should not appear blurred until the absence of the higher harmonics can be detected. Under such a scheme, moving (or low contrast) images may appear sharp since the visual system is unable to resolve high frequencies and hence cannot know that they are absent. Thus, some "error" (loss of higher spatial frequencies) is compensated for by the visual system in a manner similar to the changes of contrast gain with spatial frequency that are presumed to underlie contrast constancy for static images (Georgeson & Sullivan, 1975).

Secondly, Ramachandran *et al.* (1974) suggested that "*. . . apparent movement actually deblurs the image through some peripheral mechanism*". More recently, several models of motion deblurring have been proposed (Burr *et al.*, 1986; Anderson & Van Essen, 1987; Pääkkönen & Morgan, 1994). These models have been proposed in order to account for the *absence* of motion blur that would be expected upon the basis of the slow temporal response of the visual system (Barlow, 1958; Legge, 1978). For instance, vernier acuity is not degraded for image motion up to 3 deg sec^{-1} (Westheimer & McKee, 1975). In essence, recent models of motion deblurring assume that positional uncertainty for moving images may be maintained by effectively stabilising the neural image. For instance, Anderson and Van Essen (1987) have suggested that "shifter circuits" may dynamically alter the relative alignment of input and output neural arrays, whilst preserving local spatial relationships. Burr *et al.* (1986) suggest that blurring may be eliminated if the orientation of spatiotemporally oriented receptive fields is coincident with the velocity of an object. More recently, Pääkkönen and Morgan (1994) have suggested that the oriented spatiotemporal receptive fields proposed by Burr *et al.* are the result of a

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combination of velocity-dependent linear spatial filtering and equivalent intrinsic blur (Levi & Klein, 1990). However, whilst motion deblurring models would indeed reduce motion smear introduced by temporal sampling, they do not appear to account for the finding that blurred images appear sharper when drifted. According to such models, a drifting blurred image would not suffer further degradation but, also, would not be sharpened. One possibility is that a motion deblurring mechanism "overcompensates" for the effects of motion blur. However, it is not clear how current deblurring models could introduce such overcompensation.

An alternative interpretation is that some non-linearity gives rise to the addition of higher spatial frequency components in the effective neural image which are not present at earlier stages of processing. In the limiting case, such a non-linearity could exclusively account for the lack of blurring in human motion perception and render "deblurring" mechanisms unnecessary.

We reasoned that if sharpening was due to a non-linearity which introduced additional higher frequencies into the neural image, then reducing the sensitivity of the visual system to higher spatial frequencies should reduce the sharpness of the image. However, if sharpening reflects the assumption that moving images are sharp until there is sufficient resolution to detect that high spatial frequencies are absent (the "sharpness constancy" hypothesis), attenuating the sensitivity to high spatial frequencies will make their absence even harder to detect. In this case, reducing the sensitivity to high spatial frequencies should increase the sharpness of an image. In order to test these possibilities we have measured the perceived blur of sinusoidal gratings of various drift speeds by matching to a static blurred "square wave" before and after adaptation to a missing fundamental (MF) pattern. The MF pattern is derived from a square waveform by subtracting its fundamental sinusoidal component, the relevant characteristic of the MF pattern being that it is a high pass filtered square wave grating. Thus the resultant waveform comprises the odd harmonics 3f, 5f, 7f. etc. We have assumed that adaptation to a MF pattern should selectively attenuate the sensitivity to high spatial frequency components of an image, whilst negligibly affecting sensitivity to low spatial frequency components.

METHOD

Apparatus and stimuli

Stimuli were generated by a grating generator (Millipede VR1000) under the control of a PC microcomputer and were presented on a Hewlett Packard 1332A X–Y display with white (P4) phosphor using a raster technique at a frame rate of 122 Hz. The mean luminance of the display was 16 cd/m^2. The monitor was calibrated carefully and the image was gamma-corrected using a look-up table. The screen was masked to provide two rectangular apertures (each 2 deg vertically $\times$ 4 deg horizontally) one above the other and separated by a thin (0.25 deg) dark strip with a central fixation spot of the same mean luminance as the display. Images were presented on alternate frames in each window, under the control of a Constable Image Generator. The resultant image update rate was 61 Hz. The display was viewed from a distance of 1.14 m. The room was lit at a constant level of approximately 2 cd/m^2.

The test stimulus was a 1 c/deg sine grating whose drift speed and contrast were varied. The grating was drifted at either 0, 1.8 or 7.2 deg/sec. The match stimulus was a static 1 c/deg grating whose blur was manipulated. The blur of the match grating was intermediate between that of a square grating and a sine grating. This was achieved by replacing each of the sharp edges of a square grating with half cosine wave luminance profiles (see Fig. 1). The blur width (defined as half the period of the cosine wave blurring function) of the blurring function was increased to increase blur. Thus a blur width of 0 arcmin for the match grating was a square wave and 30 arcmin blur width was a sine-wave; intermediate widths represented intermediate blur. The adapting stimulus comprised two MF patterns of 50% contrast which were counterphased by drifting each in an opposite direction at a rate of 0.25 deg sec^{-1} to avoid afterimages and direction specific adaptation.

Procedure

The procedure was a Type B match guided by a staircase. The subject was seated at the required viewing distance and instructed to fixate the central spot throughout the run. Before the start of the experiment, a blank, mean luminance field was presented for 1 min. Subsequently a tone sounded to signal the start of the experimental trials. The subject was instructed to press either of two response buttons when ready, which initiated the run. Two seconds after the button press, in one window (at random between runs) the adapting pattern was presented, the other window was a blank field of the same mean luminance. The adapting pattern was presented for 90 sec prior to the first trial and for 10 sec prior to subsequent trials. After the adapting period, a blank field of the same mean luminance was presented for 500 msec. Then, the test sine grating was presented in the same window as the adapting pattern and the match pattern was presented simultaneously in the other window for 500 msec. The onset and offset of all patterns was abrupt. The contrast of the test and match gratings was equal and either 10, 30 or 50%. The drift speed of the test grating was set at the beginning of each run and was constant throughout the run. Direction of movement was varied randomly from trial to trial to minimise the effects of adaptation to the motion. Subjects were required to indicate which pattern appeared more blurred by pressing a button. There was a 500 msec inter-trial interval in which a blank mean luminance field was presented. On each trial, the blur of the match grating was set according to a modified PEST routine (Taylor & Creelman, 1967) designed to converge on the 75% point i.e., the blur width at which the static match grating appeared sharper on

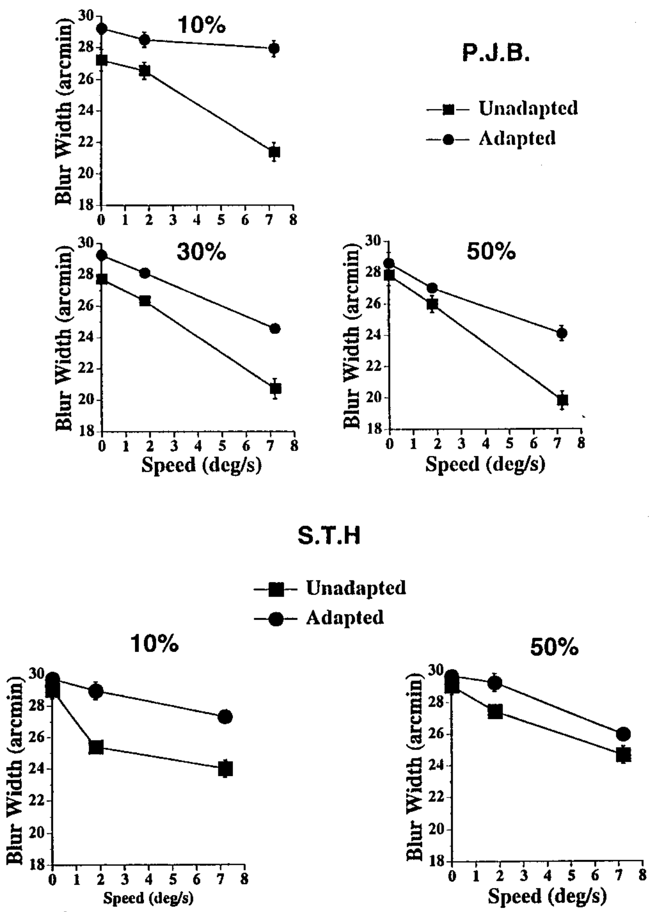

FIGURE 1. The degree of blur of the square wave pattern (expressed in arcmin) at which it appeared sharper than the sine wave (referred to here as blur width discrimination threshold) plotted as a function of the speed of the sinusoidal grating for two subjects before and after adaptation to a MF pattern. Results are shown for test contrasts of 10, 30 and 50%. Error bars represent +/−1 S.E.M.

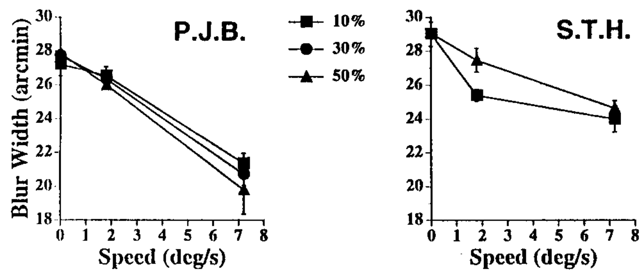

FIGURE 2. The unadapted blur width discrimination thresholds are replotted for three test contrasts. The results indicate relatively little change in thresholds for the contrasts tested. Error bars represent +/−1 S.E.M.

75% of trials. The 75% point for each match width was estimated by fitting a psychometric function (Weibull, 1951). The contrast of both test and match gratings and the drift speed of the test grating were constant for each run of 30 trials, but both were manipulated between runs. There were four identical runs for each subject for each condition, the mean and standard error of which were calculated. Trials conducted for the various contrasts and drift speeds were randomly interleaved for each subject. The adapting and test patterns were presented in the upper window for two runs and in the lower window for two runs to minimise hemifield differences. In the control conditions, the whole procedure was repeated, such that the adapting pattern was replaced by a blank field of the same mean luminance. In an auxillary experiment the perceived contrast of a drifting sinusoidal grating was measured before and after adaptation to the MF pattern. The apparatus was the same as that of the main experiment. A static grating was presented in one window and a drifting grating was presented in the other. The subject's task was to indicate which pattern had the greater contrast. The contrast of the static grating was varied using a PEST routine set to converge on the 50% point. The 50% point was estimated by fitting a psychometric function (Weibull, 1951); the mean of three such estimates was taken as the point of subjective equality. Viewing was binocular with natural pupils. Subjects used a chin rest. Both subjects (the authors) had a visual acuity of 6/6 or better, with no history of ocular ill health.

RESULTS

Figure 1 shows the results of the matching experiment for both subjects. The degree of blur of the square wave pattern (expressed in arcmin) at which it reliably appeared sharper than the sine wave is referred to here as a discrimination threshold and is plotted as a function of the speed of the sine wave grating. For stationary sinusoids, the subjects could reliably discriminate the blurred square wave for blur widths around 27–29 arcmin. However, for sinusoids drifting at 7.2 deg sec^{-1} reliable discrimination required a much sharper comparison pattern (around 20–24 arcmin). A decrease in blur width thresholds represents a *sharpening* of the blurred square wave. Thus subjects required sharper patterns in order to discriminate a sinusoid under drift conditions. This effect is smaller but consistently present at the intermediate drift speed of 1.8 deg sec^{-1}. This trend in the results is evident at all contrasts tested. After adaptation to the MF pattern, the decrease in blur width thresholds at high speeds is reduced for both subjects and at all contrasts tested. This reduction in the effect of drifting gratings is evident at all contrasts, but appears strongest at lower contrasts. There is some evidence for a small reduction in blur width threshold after adaptation for the static condition for one of the subjects (P.J.B.). However, the effect for stationary patterns is much smaller than that for drifting patterns for this subject and not evident at all in the results for the other subject.

Figure 2 re-plots the results of the non-adaptation conditions. The graph shows that there is little or no effect of test contrast on blur discrimination thresholds. Figure 3 shows the results of an auxillary experiment (subject S.T.H.) which measured the effect of adaptation to the MF pattern on the perceived contrast of a 50%

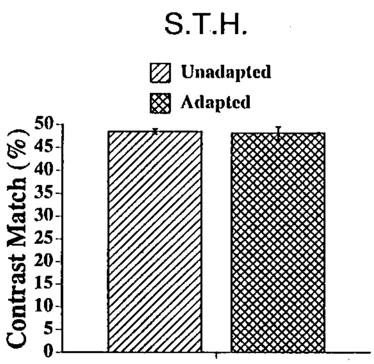

FIGURE 3. The perceived contrast of a drifting grating (7.2 deg sec^{-1}) is shown before (diagonal stripes) and after (cross-hatching) adaptation to an MF pattern. Error bars represent +/−1 S.E.M. The subject was S.T.H.

grating, which drifted at 7.2 deg sec^{-1}. The results indicate that there is little reduction in the perceived contrast of the grating after adaptation.

DISCUSSION

The results indicate that the perceived blur of a drifting sinusoidal grating is dependent upon its drift speed. At high drift speeds a drifting sine grating is sharpened. After adaptation to an MF pattern, this effect is attenuated. It seems reasonable to assume that the reduction in match widths for moving gratings reflects a perceptual sharpening of the drifting sinusoid. Such an assumption is consistent with both the subjects subjective reports and Bex and colleagues' (1995) finding, using a matching protocol, that drifting gratings appear less blurred than static ones. This sharpening with speed is reduced after adaptation to an MF pattern. One possibility is that this reduction in sharpness after adaptation is due to a reduction in the perceived contrast of the moving grating. However, Fig. 2 indicates that the differences in unadapted blur width thresholds for 10, 30 and 50% are much smaller than the differences in thresholds between the adapted and unadapted conditions. For instance, the difference in blur thresholds for 10 and 50% test contrasts at 7.2 deg sec^{-1} is less than 2 arcmin for subject P.J.B. and less than 1 arcmin for subject S.T.H. Whereas the difference in thresholds for a 50% test before and after adaptation is over 4 arcmin for P.J.B. and 1.3 arcmin for S.T.H. Thus, for the change in blur threshold to be solely accounted for in terms of changes in perceived contrast, one must posit that the perceived contrast of the 50% test is below 10% after adaptation. In order to test this possibility, we conducted an auxillary experiment which measured the effect of adapting to the MF pattern on perceived contrast of the test. Figure 3 shows that there is little or no effect of adaptation on the perceived contrast of a grating drifting at 7.2 deg sec^{-1}. Thus, the reduction in blur width thresholds after adaptation cannot be interpreted as a result of a reduction in the test grating's perceived contrast. Bex *et al.* (1995) have also shown that the perceived sharpening they found cannot be explained in terms of changes in perceived spatial frequency with motion (Parker, 1983).

One suggestion was that a default condition may be to assume that all edges are sharp and hence an object should not appear blurred until the absence of the higher harmonics can be detected. The prediction of this approach would be that adaptation to high spatial frequencies would make their absence even more difficult to detect and hence, the image should appear sharper. The results fail to support this prediction. Alternatively, sharpening might be explained by postulating that some non-linearity serves to introduce additional higher frequencies into the neural image, which subsequently enhances sharpness. The effect of any such non-linearity would be attenuated by adapting to an MF pattern and thus result in a reduction in perceived sharpness. Such a scheme is consistent with our finding of increased thresholds after adaptation. It is also consistent with our finding that this effect is greatest at low test contrasts if one assumes that higher frequencies introduced by a physiologically plausible non-linearity are likely to be represented at lower contrasts than the fundamental.

To summarise, current models of motion deblurring do not account for the phenomenon of sharpening. Thus, the question arises as to whether sharpening and deblurring are derived from a unitary mechanism or are discrete processes. If sharpening and deblurring are discrete processes then any interactions between them must be taken into account in the interpretation of their respective measures. Alternatively, the phenomena may be intricately related such that one is a special case of the other. Indeed, in the limiting case, it may be that the relative lack of blurring in human motion perception may be solely due to a non-linearity which introduces higher frequencies to the neural image. If both sharpening and deblurring are derived from the same neural processes then future models must posit a unitary mechanism which may account for both phenomena. Our results are commensurate with a non-linearity in motion processing that serves to introduce higher frequencies into the effective neural image. We are currently investigating whether such a non-linearity may also be implicated in the more general case of motion deblurring.

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