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Sharpening of Drifting, Blurred Images

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The perceived blur of moving images is less than expected given the sluggish temporal response of the visual system. This suggests that a motion deblurring mechanism may exist to preserve the positional acuity and sharpness of moving images. Furthermore, when sequences of blurred stills are presented, observers report that the moving image is in sharp focus raising the possibility that there is a mechanism which may sharpen the appearance of moving, blurred images. We have measured the effects of velocity and contrast on the perceived blur of drifting, blurred images (sine gratings and blurred edges). Subjects matched the perceived blur of drifting, blurred images to that of static, blurred images in a dimly lit room. It was found that perceived blur was inversely related to drift speed and contrast. The results confirm that moving, blurred images may appear sharper than when they are static. This finding is not consistent with some models of motion deblurring since these account only for the preservation of sharp contours that are present in the image and not for the sharp appearance of images that are in fact blurred.

Blur Deblurring Edges Sine gratings Sharpening

INTRODUCTION

According to several estimates, the visual system integrates information over approx. 120 msec in daylight (Barlow, 1958; Legge, 1978). Therefore, the position of moving objects will change during the integration period, and this should result in positional uncertainty and smearing. This means that moving images should appear blurred and that these problems should increase with target velocity, as occurs in photographs taken with a camera at low shutter speeds. The fact that human observers usually see moving images in sharp focus has lead several researchers to suggest that motion processing in the human visual system may reduce the blur of moving images (Burr, 1980; Burr, Ross & Morrone, 1986; C. H. Andersen & Van Essen, 1987; Martin & Marshall, 1993). The purpose of motion deblurring in these models is to accurately identify the location and spatial structure of moving objects.

For normal observers, motion deblurring has been reported for moving sharp images by several researchers; e.g. Burr (1980). Furthermore, it has been commented that under certain conditions, drifting blurred images may appear sharper than when they are static: when sequences of blurred stills are presented in apparent motion, observers report that the moving image is in sharp focus. However, if presented alone for the same duration, each still appears blurred (Ramachandran, Madhusudhan, Ras & Vidyasagar, 1974). This suggests that low quality drifting images may be sharpened to yield a superior quality to the original image. Such sharpening is distinct from motion deblurring, in that motion deblurring restores positional acuity and spatial structure whereas sharpening alters the perceived spatial structure of the moving image.

There is some evidence which questions whether motion deblurring occurs for all images and under all conditions. For drifting, blurred squares, Prather and Ramachandran (1991) demonstrated that deblurring occurred only on moving edges orthogonal to the direction of motion, since these edges appeared sharper than the edges aligned along the axis of motion. Additionally, Morgan and Benton (1989) found that whilst vernier hyperacuity remains unaffected by a retinal velocity of up to 3 deg/sec, the threshold for discriminating the spacing between two bars (spatial interval acuity) is degraded significantly by motion. The authors claim that this is evidence that deblurring is not a general process. However, as C. H. Andersen and Van Essen (1990) observe, motion results in only a modest degradation in spatial interval acuity when compared with spatial blur (Levi & Klein, 1990). Moreover, in the task employed by Morgan and Benton, at greater velocities, the stimulus is present in the central visual field for a shorter period. When this problem is avoided using jitter, there is

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minimal degradation in performance even for large amounts of jitter (Badcock & Wong, 1990).

There is, therefore, considerable evidence for a mechanism that reduces the perceived blur of moving, sharp images. The distortion of a blurred image into a sharper image, when moving, is not a well documented effect and it is unclear how such a process may operate. Ramachandran *et al.* studied the perceived blur of moving pictures; however, it remains unclear whether all blurred images would be sharpened when moving. The precise effects of velocity and contrast on such sharpening have not been extensively explored and the generality of the process is not yet well established. If all moving, blurred edges are sharpened, then a drifting sine-wave grating should appear sharper. Its appearance should become distorted and look more like a square-wave grating as it moves. Similarly, a drifting, blurred edge should resemble a sharper edge. We have investigated the changes in perceived blur of drifting sine gratings and drifting edges with changes in velocity and contrast. It was hypothesized that a progressively sharpened sine-wave grating would more closely approximate a square-wave grating in appearance. Therefore, the perceived blur of a drifting sine-wave grating was compared to that of a static grating whose blur was intermediate between that of a sine-wave grating and that of a square-wave grating.

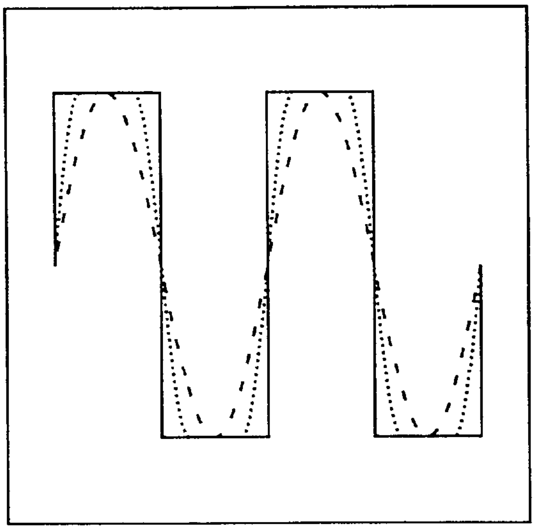

FIGURE 1. This figure illustrates the manipulation of the blur of the static match grating. The blur of the square wave (solid line) was manipulated by replacing its sharp edges with half-cosine wave blur profiles centred on the edge, as shown by the broken lines. The spatial frequency of the square wave was 1 c/deg. Maximum blur was a sine wave. (blur space constant = 30 arc min; bold dashed line), minimum blur was a square wave (blur space constant = 0 arc min; solid line), intermediate blur is shown by the dotted line.

EXPERIMENT 1: EFFECTS OF VELOCITY ON THE PERCEIVED BLUR OF A DRIFTING SINE GRATING

Subjects

The subjects in all experiments were one of the authors (PB) and one naive observer. All had a visual acuity of 6/6 or better, with no history of ocular ill health.

Apparatus

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 122 Hz frame rate. 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 × 4 deg horizontally) one above the other and separated by a thin (0.25 deg) dark strip with a bright, central fixation spot. 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, dim level.

Stimuli

The test stimulus was a 1 c/deg sine grating whose drift speed and contrast were varied. 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 width of the blurring function (defined as half the period of the cosine) was increased to increase blur. Thus with a blur width of 0 arc min, the match grating was a square wave and with a blur width of 30 arc min, it was a sine wave; intermediate widths produced intermediate blur.

Procedure

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 the screen was a blank, mean luminance field for 1 min to ensure a constant state of adaptation. At the end of the minute 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 and for 500 msec, in one window (at random) the drifting sine grating was presented, while simultaneously in the other window, the static match grating was presented. The contrast of the two 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 minimize the effects of adaptation. Subjects were required to report, by pressing a button, which grating appeared more blurred: the static grating or the drifting grating. There was a 2-sec inter-trial interval in which a blank mean luminance field was displayed. This was followed by the next trial. The blur of the match grating on each trial was set according to

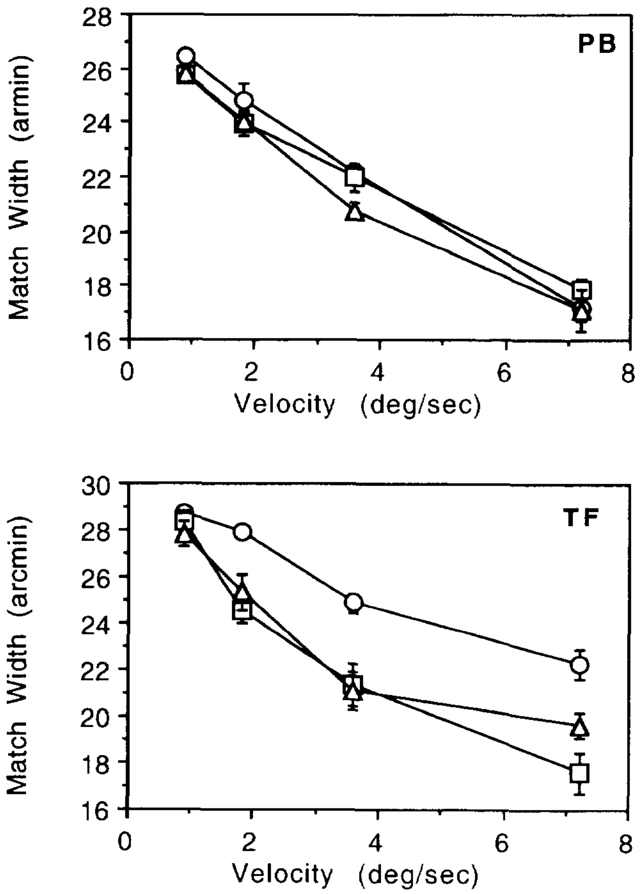

FIGURE 2. Blur space constant of the static, match grating at which the perceived blur of a drifting sine grating was matched with a probability of 50%. The drift speed of the sine grating is shown on the abscissa. The contrast of both gratings was 10% (○), 30% (□) or 50% (△). Error bars represent ±1 SE.

a modified PEST routine (Taylor & Creelman, 1967) designed to converge on the 50% point, i.e. the blur width at which the subject reported seeing greater blur of the drifting grating on 50% of trials. The 50% point for each match width was inferred by fitting a psychometric function (Weibull, 1951). The contrast of both 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 match gratings were randomly interleaved for each subject. Match widths were not recorded for a static sine grating (0 deg/sec) because maximum blur of the match grating (30 arc min) was a sine grating and it would have been possible to record only half a psychometric function.

Results and discussion

The widths of the blur function at which the blur of the static grating matched that of the drifting sine grating (referred to as the match width) are shown for each subject in Fig. 2. Match widths below 30 arc min indicate that the perceived blur of the sine grating was less when drifting. It can be seen that at all velocities, the sine grating appeared less blurred when drifting than when static, i.e. the grating was sharpened. Furthermore, its perceived blur was inversely related to velocity suggesting that sharpening increased with velocity.

Perceived spatial frequency has been shown to increase with velocity. Initially, a sudden doubling of spatial frequency was observed for phase reversing sine gratings at high temporal modulation rates (Kelly, 1966). Subsequent research has shown that there is a progressive increase in spatial frequency as a function of temporal frequency for both phase reversing (Richards & Felton, 1973; Virsu, Nyman & Lehtio, 1974; Kulikowski, 1975) and drifting gratings (Parker, 1981, 1983). Since the luminance gradient of sine gratings increases with spatial frequency, it may be argued that the increase in apparent sharpness with velocity reflects an increase in luminance gradient as the perceived spatial frequency increases. However, for drifting sine gratings of a range of spatial frequencies, Parker (1983) observed a maximum spatial frequency shift of approx. 20%. This was found at 20 deg/sec for a 1 c/deg sine grating. The width of the blur of a 1.2 c/deg sine grating is 25 arc min whereas the match widths in the present experiment were as little as 17 arc min and at a lower drift speed (7 deg/sec). This suggests that motion sharpening does not simply reflect an increase in perceived spatial frequency.

EXPERIMENT 2: EFFECTS OF CONTRAST ON THE PERCEIVED BLUR OF A DRIFTING SINE GRATING

Introduction

It has been shown that the perceived contrast of drifting gratings is inversely related to velocity (Thompson, 1982). In Expt 1, the physical contrasts of the gratings were equal, but the test grating was drifting in all conditions. This means that its perceived contrast (and perhaps mean luminance gradient) may have been lower than expected. If perceived blur is related to the mean luminance gradient of a blurred edge, then the sharpening of the test grating in Expt 1 may have been under-estimated in some conditions.

For static sine gratings, Georgeson and Freeman (1993) have shown that low contrast edges do not look more blurred than high contrast edges, even though the mean luminance gradient increases with contrast. These researchers demonstrate that perceived blur may be reliably predicted from the ratio between the first and third spatial derivatives, which is invariant with contrast. If this relationship holds for drifting blurred images, then perceived blur should be unaffected by contrast. In order to examine whether perceived blur is affected by contrast for moving images, blur match widths were measured as described in Expt 1 but drifting sine gratings of different contrasts were compared to a static match grating of a fixed contrast.

Method

Stimuli and procedure were as in Expt 1 except that the contrast of the static match grating was always 30% and the perceived blur of this stimulus was compared to a drifting test grating of contrast in the range 10% to 50% at 10% intervals.

Results and discussion

The match widths are shown for each subject in Fig. 3. Subjects are able to make a consistent judgement of perceived blur even when contrast (luminance gradient) differs broadly. It can be seen that the match width is inversely related to contrast. This result demonstrates that although perceived blur may be invariant with contrast or luminance gradient for static images (Georgeson & Freeman, 1993), it is affected by contrast for moving images. The gradient of the function is shallower for the slower moving test gratings. This trend suggests that for static images, contrast may have little or no effect on perceived blur, consistent with Georgeson and Freeman (1993).

The results suggest that perceived blur of drifting images may involve an estimation of the rate of change in local luminance gradient. Similarly, Mather (1987) and Moulden and Begg (1987) have measured the threshold for discriminating the direction of displacement of a blurred edge. Both groups of researchers found that thresholds were affected by contrast and the size of the displacement. The relationship was found to be a function of the rate of change in luminance.

Burr and Ross (1982) measured motion thresholds for gratings and bars drifting at high speeds. It was found that peak sensitivity to drifting gratings was approximately equal in terms of temporal frequency (at *c.* 10 Hz). This result suggests that perceived contrast may increase near threshold, for drifting gratings. We have shown that perceived blur of drifting images may involve an estimation of local luminance gradient, hence it might be argued that motion sharpening may simply reflect an increase in perceived contrast at high speeds. However, at supra-threshold contrasts, it has been shown that perceived contrast and velocity are inversely related (Thompson, 1982), the opposite relationship to that at threshold. Additionally, for static images, Georgeson and Sullivan (1975) reported that the perceived contrast of supra-threshold static images was invariant over a range of spatial frequencies despite broad differences in contrast sensitivity at threshold. It is therefore unlikely that any simple relationship between the perceived contrast and drift speed may account for motion sharpening.

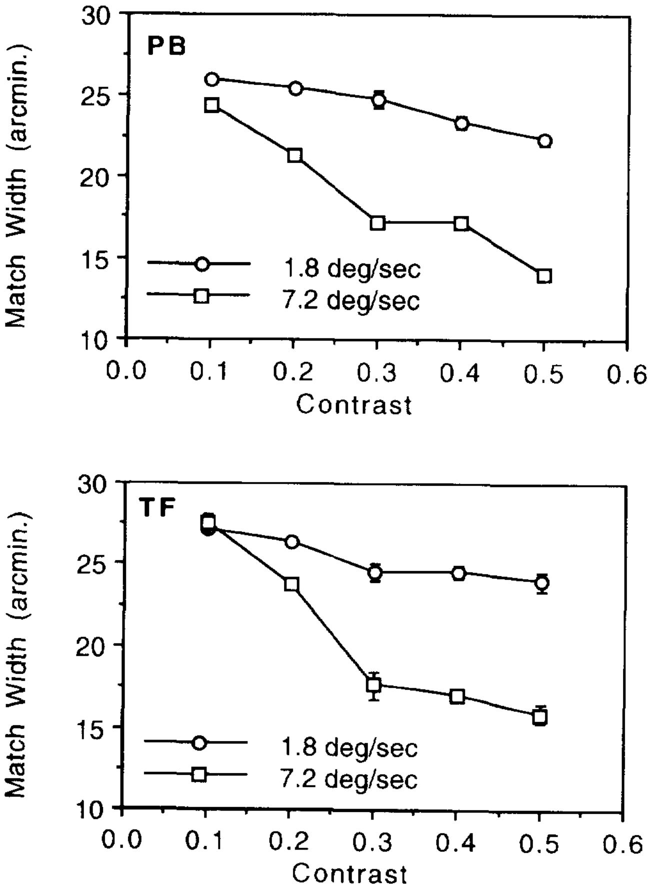

FIGURE 3. Blur space constant of the static, match grating at which the perceived blur of a drifting sine grating was matched with a probability of 50%. The drift speed of the sine grating is shown in the legend. The contrast of the static match grating was 30%, the contrast of the drifting test grating is shown on the abscissa. Error bars represent ±1 SE.

EXPERIMENT 3: THE PERCEIVED BLUR OF DRIFTING, BLURRED EDGES

Introduction

The above results demonstrate that the perceived blur of a sine grating is less when it is drifting than when it is static and that its perceived blur is inversely related to drift speed. This suggests that motion sharpening occurs for drifting sine gratings as well as for complex images and that motion sharpening increases with velocity. When a sine grating drifts past a given point, there are periodic increases and decreases in luminance. Pääkkönen (1993) has recently reported that the perceived blur of a drifting Gaussian blurred edge depends on the contrast polarity of the edge. For edges with 4 arc min blur width, drifting at 4 deg/sec, edges with the bright end leading appeared more blurred than edges with the dark end leading. This finding was interpreted as evidence for a non-linearity in mechanisms analysing the form of moving objects. This finding is consistent with the differences between the response times of photoreceptors to light increments and their response times to light decrements which have been reported by Hayhoe, Benimoff and Hood (1987). The results of Expt 1 suggest that both the leading and trailing, blurred edges of Pääkkönen's stimuli may have been sharpened. However, the perceived blur of Pääkkönen's edges was not compared to that of a static edge and it remains unclear whether motion sharpening had occurred and how the polarity of luminance change affects such sharpening. Therefore, the perceived blur of a drifting, blurred edge was measured and the effects of the polarity of the luminance change on perceived blur was examined.

Method

Apparatus and procedure were as in Expt 1. The match stimulus was a static, blurred edge, the test stimulus was a drifting, blurred edge. The blur was manipulated as before by replacing a sharp luminance step with a half-cycle cosine wave and by varying the spatial frequency of the cosine function. The blur width of the static match edge was set at the beginning of each run at either 15 or 30 arc min. The blur width of the drifting test edge was set between trials according to a modified PEST procedure (Taylor & Creelman, 1967). Note that in Expts 1 and 2, the blur of the match edges was manipulated, not that of the test edge. The velocity at which the test edge was drifted was constant on a particular run. Randomization of the direction of motion would have affected the polarity of the luminance change of the drifting edge; therefore, direction of motion was constant on a particular run and the two directions of motion were examined separately. Subjects were required to indicate which edge appeared more blurred, the drifting or the static edge. The particular window in which the edges appeared on each trial was selected at random except when the test edge was static. On these trials, the subject was informed in which window was the test edge and was required to indicate in which window was the more blurred edge. The test edge was in the upper window for two runs and in the lower for two runs to minimize hemifield differences. The blur width at which subjects reported seeing equal blur of the two edges with a probability of 50% was inferred by fitting a psychometric function (Weibull, 1951) to the data. There were 30 trials per run and four runs for each condition, the mean and standard error of the four runs were recorded.

Results and discussion

The blur width at which subjects reported seeing equal blur with a probability of 50% is shown in Fig. 4 for each subject for each blur width, contrast, drift direction and drift speed. The data for conditions in which luminance increased with the displacement of the blurred edge are compared in each graph with the data from the corresponding condition in which it decreased. It can be seen that the width of the blur function of the test edge increases with velocity for each blur width recorded, i.e. sharpening has occurred for the drifting, blurred edges. Note that the width of the drifting edges were manipulated between trials, while the width of the match edge was fixed at either 15 or 30 arc min, hence in this case the function rises when sharpening has occurred.

The data demonstrate that sharpening occurs for a single, drifting, blurred edge and that the sharpening increases with velocity. For one observer (PB) the perceived blur of edges where luminance fell with displacement appeared slightly more blurred than those where luminance rose, consistent with results of Pääkkönen (1993) in dim light. However, the effect is not found for the second observer. The failure to observe a consistent difference between the direction in which the edges were drifted shows that sharpening is approximately equal (or not consistently unequal) for luminance gradients which increase with displacement and for those which decrease with the displacement of the edge. This finding demonstrates that the direction of the change in brightness does not consistently affect the perceived blur of a drifting edge and that motion sharpening may be insensitive to the polarity of luminance change at the edge of a drifting object.

GENERAL DISCUSSION

The results demonstrate that the perceived blur of sine-wave gratings and blurred edges is less when drifting than when static. The perceived blur of these images decreases with velocity. High contrast, drifting gratings appear less blurred at a given drift speed than low contrast, drifting gratings. The data confirm, extend and quantify the finding that blurred images can appear sharper when in apparent motion (Ramachandran *et al.*, 1974). For moving, sharp images, motion deblurring only removes some of the motion smear; there remains some smear, but it is less than should occur given the temporal response of the human visual system (Burr, 1980). In contrast, for drifting blurred images, not only is the motion smear removed, but also some of the blur present in the original stimulus is removed.

Relation to existing models

A number of models have been proposed in an attempt to explain how motion deblurring may operate. C. H. Andersen and Van Essen (1987) suggest that motion deblurring may be mediated by neural "shifter circuits". These circuits allow for a dynamic shift in the relative alignment of input and output neural arrays under the control of inhibitory neurones. The strategy introduces a compensatory cortical shift whose velocity is equal and opposite to the locally measured retinal velocity. Thus a coherently moving image is transformed to a stabilized image. This delay of image processing effectively allows additional image analysis. The additional image analysis would eliminate some of the camera-like motion smear and allow a more accurate representation of the spatial structure of a moving image.

Burr (1980) and Burr and Ross (1986) propose that the visual system has neurophysiological properties which enable it to analyse form and motion simultaneously. This may be mediated by extended temporal summation of images in motion. Burr *et al.* (1986) observe that for a receptor with a non-oriented spatio-temporal receptive field, the longer the summation period, the greater the smear arising from motion (as for a camera with a low shutter speed). However, for a motion detector whose receptive field is oriented in time, image motion will be effectively annulled, such that analysis will be the same as for stationary images, but in x–t space rather than x–y space.

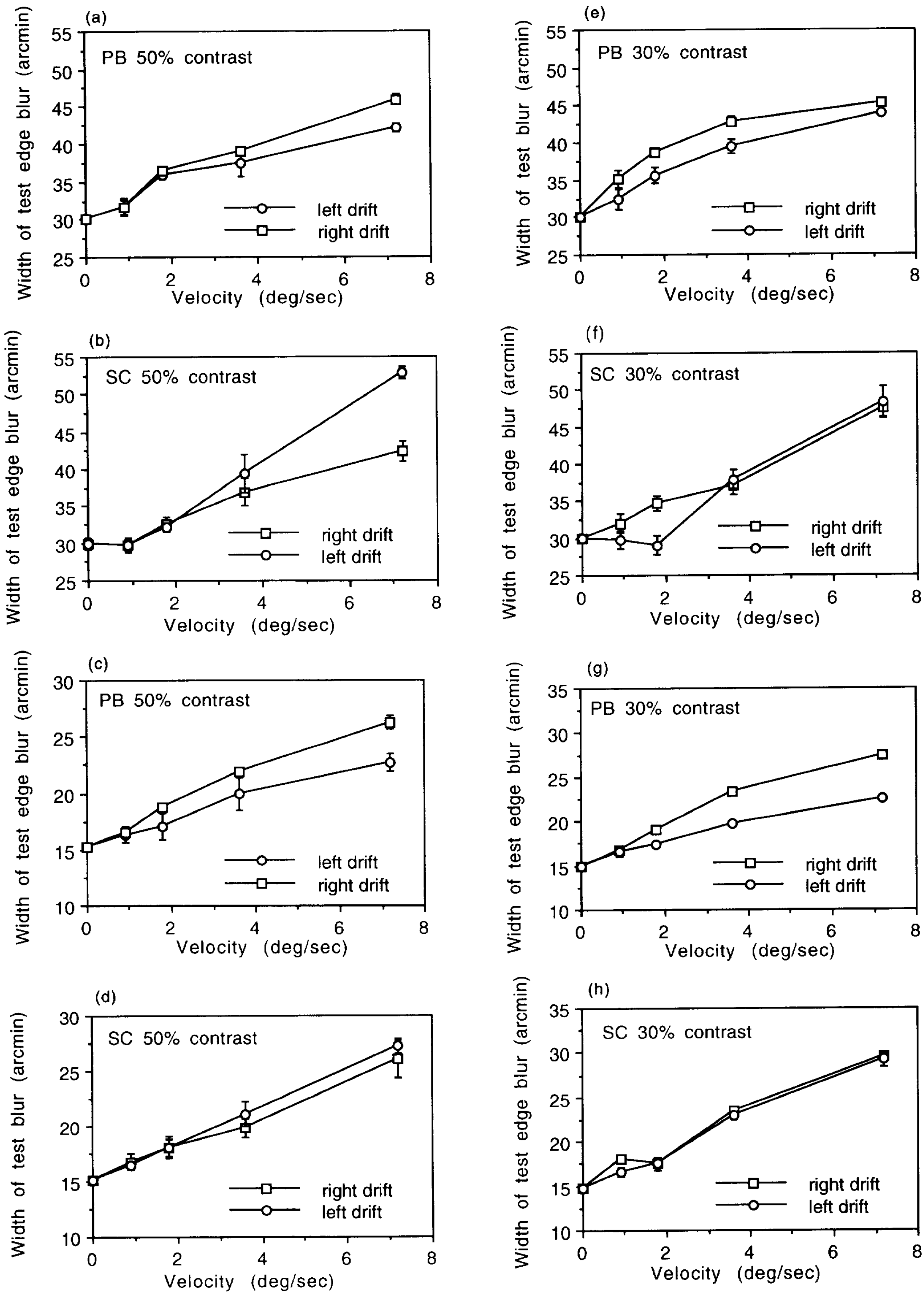

FIGURE 4(a–h). *Caption opposite.*

Pääkkönen and Morgan (1994) have recently proposed a model which attempts to account for the simultaneous effects of spatial blur and motion blur. The authors report that blur discrimination thresholds for moving, Gaussian blurred edges increase with velocity approximately linearly and the slope of this increase is inversely related to the space constant of the blurring function. It is assumed that the internal representation of a blurred edge is determined by the convolution of the physical blur of an edge, a static spatial filter and a velocity-dependent spatial filter. The static spatial filter corresponds to the smallest receptive field size of spatial filters in the human visual system and introduce equivalent intrinsic blur (Levi & Klein, 1990). It is argued that the data are well fitted by a model in which the velocity-dependent spatial filter arises from linear (camera-like) motion smear. The integration period of the motion smearing temporal filters is consistent with previous estimates (Burr, 1980). In this model, the oriented, receptive fields proposed by Burr *et al.* (1986) are not the receptive fields of single mechanisms, but the result of these two separable filters. Thus the motion receptive fields may be descriptive functions of how the temporal impulse response of the visual system and velocity modify the appearance of the underlying spatial filter in space–time co-ordinates.

The shifter circuits proposed by C. H. Andersen and Van Essen (1987) can account for the removal of motion smear in sharp images. However, the model is unable to explain the apparent sharpness of drifting blurred images. This system would only permit temporally extended analysis of drifting images, removing some of the internal noise and motion smear. It cannot explain the sharp appearance of drifting, blurred images. The arrangement of spatio-temporal receptive fields proposed by Burr *et al.* (1986) or by Pääkkönen and Morgan (1994) are similarly unable to account for the sharpening reported here for drifting, blurred sine gratings and edges. The image analysis proposed would at best permit the spatial structure of the original image to be veridically represented. Again, it predicts the sharp perception of moving, sharp images but not of images lacking sharp edges.

A neural network model has recently been proposed to account for the elimination of motion smear by local inhibition (Martin & Marshall, 1993). The fact that motion smear increases with exposure duration below 30 msec and then decreases until a moving object is sharp at 100 msec (Burr, 1980), suggests that the behaviour of processing mechanisms differs in the early stages (when smear is present) than at later stages of processing (when smear is absent). Martin and Marshall (1993) developed a self organising neural network in which long-range excitatory horizontal intrinsic connection (LEHICs) integrate motion non-locally. The network laterally propagates a predicted trajectory of motion to successive image locations where a stimulus is likely to appear. LEHICs generate excitatory signals along the predicted trajectory. The accumulating activation of excitatory inputs from LEHICs and from the stimulus itself let neurones further along the trajectory suppress (via lateral inhibition) the activation of neurones carrying the smear. The comet-like tail of smear contracts progressively and the representation of a moving target sharpens. The model predicts that motion deblurring increases with the coherence of a trajectory. In this model, LEHICs would inhibit motion smear and spatial smear equivalently, thus sharpening the appearance of drifting, blurred images.

Alternatively, S. J. Anderson (1993) has recently demonstrated that delays in the processing of higher spatial frequency harmonics may alter the appearance of drifting compound wave forms. Consequently, the phase of higher harmonics must be advanced in order for the waveform to appear the same when drifting as when static. Furthermore, the results demonstrated that the phase lags were greater if the component gratings were in cosine phase (bar) rather than in sine phase (edge). These results suggest that the human visual system may assume that drifting images are sharp, unless there is sufficient resolution to determine that an image is blurred. This is supported by Anderson's observation that drifting triangle waves appear as square waves. When stimuli are in motion, some of the higher harmonics can no longer be resolved (Burr & Ross, 1982) and the visual system is incapable of discriminating between a sharp object and a blurred object. The present data suggest that the 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.

CONCLUSIONS

We have demonstrated that drifting, blurred images may appear sharper than when static. This effect is referred to as motion sharpening and is distinct from previously described effects of motion deblurring. Models of motion deblurring can account for the restoration of positional acuity and the sharp contours of drifting sharp images, but most are not able to account for the sharper appearance of drifting, blurred images. Motion sharpening and motion deblurring could be explained by a single model in which motion smear and spatial smear are reduced by local inhibition or by a single model in which images are always assumed to be sharp unless there is sufficient resolution to detect the absence of higher harmionics.

FIGURE 4 (*opposite*). Blur space constant at which the perceived blur of a drifting edge matches that of a static, blurred edge with a probability of 50%. The drift speed of the test edge is shown on the abscissa. □ Rightward motion (luminance fell with displacements of the edge); ○ leftward motion (luminance rose with displacements). (a)–(d) 50% contrast; (e)–(h) 30% contrast. (a, b, e, f) The match edge was 30 arc min blur; (c, d, g, h) the match edge was 15 arc min blur extent. Error bars represent ±1 SE.

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