Seeing blur: 'motion sharpening' without motion

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It is widely supposed that things tend to look blurred when they are moving fast. Previous work has shown that this is true for sharp edges but, paradoxically, blurred edges look sharper when they are moving than when stationary. This is 'motion sharpening'. We show that blurred edges also look up to 50% sharper when they are presented briefly (8–24 ms) than at longer durations (100–500 ms) without motion. This argues strongly against high-level models of sharpening based specifically on compensation for motion blur. It also argues against a recent, low-level, linear filter model that requires motion to produce sharpening. No linear filter model can explain our finding that sharpening was similar for sinusoidal and non-sinusoidal gratings, since linear filters can never distort sine waves. We also conclude that the idea of a 'default' assumption of sharpness is not supported by experimental evidence. A possible source of sharpening is a nonlinearity in the contrast response of early visual mechanisms to fast or transient temporal changes, perhaps based on the magnocellular (M-cell) pathway. Our finding that sharpening is not diminished at low contrast sets strong constraints on the nature of the nonlinearity.

Keywords: motion; edge detection; perceived blur; contrast; nonlinearity

1. INTRODUCTION

When an object moves fast across the field of view it often appears blurred. Visual responses are somewhat sluggish, and so the response to a moving edge is effectively spread out across the retinal surface. As in photography, this is 'motion smear' or 'motion blur' (e.g. Burr 1980). Paradoxically, however, when blurred images move fast they look sharper than when they are stationary, rather than looking even more blurred. This is 'motion sharpening' (Ramachandran *et al.* 1974; Bex *et al.* 1995; Hammett & Bex 1996; Hammett 1997; Hammett *et al.* 1998). We have previously shown that fairly sharp edges suffer motion blurring while more blurred ones undergo sharpening, with a transition point around 10 arcmin blur (Hammett *et al.* 1998).

Several different explanations have been offered for motion sharpening, based on different levels of visual information processing. One idea is that it represents an (over-)compensation for motion blur: when motion is detected, this information is somehow used to re-code the edge blur to offset the motion smear (Burr 1980; Anderson & Van Essen 1987; Martin & Marshall 1993). Second, motion sharpening might arise by default: at high speeds vision is unable to detect the high spatial frequencies that render edges sharply and so the visual response to sharp and blurred edges will be similar. By default, vision might presume that edges are sharp until there is reliable information to the contrary (Burr & Morgan 1997). Like the first, this hypothesis requires that motion information is used to re-interpret the available sensory information about spatial blur.

Third, at a much lower level, we have proposed a model

in which motion sharpening arises through early nonlinearity in the response of visual mechanisms (Hammett *et al.* 1998). In the primate retinocortical pathway, the magnocellular (M-cell) system responds more vigorously to high image speeds than the parvocellular (P-cell) system does (Merigan & Eskin 1986), but the response of M cells saturates at much lower contrasts than P cells do (Kaplan *et al.* 1990; Sclar *et al.* 1990). If such a compressive transducer was applied locally, at each point on the input image, the result would be a distorted—and sharpened—response to blurred edges, and this might be more evident perceptually at high speeds where M cells make a greater contribution to the neural response. This explanation also accounts quite nicely for the perceived sharpening of blurred edges in peripheral vision (Galvin *et al.* 1997), where the ratio of M cells to P cells increases (Dacey 1994).

Fourth, an alternative low-level account has recently been offered by Pääkkönen & Morgan (2001), based on linear rather than nonlinear filtering. They point out that the visual response to a briefly flashed image is biphasic—a wave of excitation followed about 50 ms later by a wave of inhibition. This biphasic impulse response model has long been known to account rather well for visual detection thresholds of low spatial frequency (blurred) images under different temporal conditions (e.g. Watson & Nachmias 1977). When a biphasic (but linear) spatiotemporal filter is applied to moving edges, it can predict both motion smear and motion sharpening, as observed experimentally (Pääkkönen & Morgan 2001). Although this linear model cannot account for the observed sharpening of purely sinusoidal moving gratings (because linear filters always transmit sine waves faithfully as sine waves), it does challenge the central role of nonlinear distortion in motion sharpening.

We note that for the first, second and fourth hypotheses (above) motion through space and time is essential to the

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Figure 1. (a) The sequence of test and comparison images. Comparison blur was adjusted across trials to find the blur that perceptually matched the test blur. Actual number of visible bars was greater than shown and increased with spatial frequency. (b) The range of possible luminance profiles from square wave to sinusoid. Blur was defined as the width (half-period) of the sine wave edge profile, in arcmin.

explanation of 'motion sharpening'. For the early nonlinearity model, however, motion is incidental. Any viewing condition that produces a dominant response from the nonlinear mechanism should produce sharpening of edges. Peripheral viewing may be one such case (see above). Here we test this reasoning in another way by presenting *stationary* blurred edges for different durations. We expect the nonlinear mechanism to respond relatively well at brief durations and so we predict perceived sharpening of briefly presented, stationary edges. Models that depend upon motion *per se* would not predict this. We also test the idea that a smooth compressive nonlinear response function is responsible for sharpening. Distortion produced by saturation at high contrasts should be much reduced at low contrasts.

2. METHODS

(a) Apparatus and stimuli

Achromatic (greyscale) grating patterns were generated by a VSG2/3W (Cambridge Research Systems) graphics board with 14 bit resolution and displayed on an Eizo 6600M monitor at a frame rate of 120 Hz. The mean luminance was 31 cd m^{-2} . The display was gamma corrected (linearized) using internal look-up tables. The test (T ms) and comparison (500 ms) gratings were displayed successively in a window subtending 18° high $\times$ 6° wide (figure 1a), with a 125 ms blank interval (a homogeneous grey screen of the same mean luminance) between the two presentations. Viewing was binocular from a distance of 57 cm, in a semi-darkened room and no head restraint was used.

The stimuli were horizontal periodic gratings whose luminance profile could vary between sine wave and square wave while the spatial period was held constant. To control the degree of blur, each edge of a square wave was replaced by half a cycle of a sine wave centred on the edge (see figure 1b; Bex *et al.* 1995). Blur width was defined as the half-period of this sinusoidal profile, in arcmin. (Note that the gratings were *not* sine waves that had been clipped or truncated in amplitude, although it might appear so from figure 1b.)

(i) Experiment 1

Five test images were used, with blur values 120, 60, 30, 15, 7.5 arcmin at spatial frequencies of 0.25, 0.5, 1, 2 and 1 cycle deg^{-1} , respectively. Thus the first four were simple sine-wave gratings, while the fifth was a partially blurred square-wave grating. Our previous work showed that edge blur, not periodicity, was the key factor in motion sharpening (Hammett *et al.* 1998). Michelson contrast was 30%. Test and comparison gratings of the same spatial frequency (but different edge profiles) were presented successively. The temporal order and spatial phase of the two patterns were randomized from trial to trial. The comparison pattern was presented for 500 ms with abrupt onset and offset and its blur was adjusted from trial to trial by a staircase procedure (modified PEST; Taylor & Creelman 1967) to match the perceived blur of the test pattern, whose luminance profile was held constant across different test durations ($T = 8, 24, 48, 96$ or 500 ms). The subject had to indicate which of the two patterns appeared sharper by pressing a button. The point of subjective equality (50% point on the psychometric function) was estimated by probit analysis (Finney 1971). Plotted points are the geometric means of three (subject S.H.) or four (subject S.B.) such estimates. Order of sessions was pseudorandom. Subjects were author (male, S.H.) and another highly practised observer (female, S.B.). Both had normal vision without correction.

(ii) Experiment 2

The procedure was very similar to experiment 1. Three test images were used, with blur values 60, 30 and 15 arcmin at spatial frequencies of 0.25, 0.5, 1 cycle deg^{-1} , respectively. Thus, all were partially blurred square-wave gratings. Display frame rate was 100 Hz. Test duration was 20 ms while comparison duration was 500 ms as before. The inter-stimulus interval was 150 ms. Test and comparison contrasts were equal (as before) but had values of 10, 15, 20, 40 and 80% in different blocks of trials. Control trials were run in which the test duration was also 500 ms. Matches here were close to veridical, as expected and the average matches (across the five contrasts) were taken as baseline values. Results are plotted for each observer as a per-

Figure 2. Experiment 1. Shows the comparison blur that appeared to match the test blur at different test durations. Briefly presented edges looked less blurred. Error bars (± 1 s.d. of the individual staircase estimates) are shown; where not seen, they are smaller than the symbol size. (a) Subject S.H.; (b) Subject S.B.

Figure 3. Experiment 1. (a) Filled circles, blur matching data (from figure 2) re-expressed as percentages of the test blur, and averaged (geometric means ± 1 s.e.) over the two observers and five test blurs. Open circles, similar results, re-plotted from Galvin *et al.* (1999), figure 2, pooled over three observers and 11 test blurs. Briefly presented edges looked less blurred by 40–50%. (b) Test blur was 30 min only. Geometric mean of observers S.B., S.H. ± 1 s.e. Sharpening was similar at high contrast (90%, squares) and medium contrast (30%, circles).

centage of the baseline values. Subjects were S.B. (as above), and another practised observer (D.S., male) who did not know the experimental hypotheses. Both had normal vision without correction.

3. RESULTS

(a) Experiment 1

Figure 2 shows the level of comparison blur needed to match each test blur, plotted as a function of test duration. It is clear for both observers and at all levels of test blur, that perceived blur decreased progressively at shorter durations. The similarity in the (log-log) slope of these functions from small to large test blurs (especially for subject S.B.) reflects approximate *scale invariance* in perception of blur. The same proportional change in blur was seen for small and large test blurs. Figure 3a shows that on average

edges looked 40–50% less blurred at brief durations (8–24 ms) than at longer durations (500 ms). Figure 3b confirms this with data from additional sessions in which the test blur was 30 arcmin and both test and comparison contrast were 90%. Results (figure 3b, squares; average of subjects S.B. and S.H.) were fairly similar to the data obtained in the main experiment for the same 30 min test blur at 30% contrast (figure 3b, circles).

(b) Experiment 2

Here we tested whether the sharpening observed at brief durations was diminished at low contrast. Figure 4 shows that it was not. Both observers showed an average of about 40% sharpening (60% blur match) for 20 ms gratings at low contrast (10–15%). These brief, low contrast stimuli were approaching the threshold of visibility, but the sharpening was, if anything, greatest at low contrast. At high

Figure 4. Experiment 2. Sharpening did not decrease at low contrast. Test 20 ms, comparison 500 ms, of equal contrast. Results for two observers (filled symbols, S.B.; open symbols, D.S.) averaged over three test blurs (15, 30, 60 min). Points are geometric means (± 1 s.e.) of 12 staircase estimates. Curves without symbols show that a compressive local contrast response (Hammett *et al.* (1998), eqn 5) cannot account for these data, either with strong contrast compression (solid curve) or mild compression (dashed curve)—see § 4. Thin solid line, model, $S = 0.2$; thin dashed line, model, $S = 2.0$.

contrast there were individual differences, in that S.B. and S.H. both showed about 40% sharpening at 80–90% contrast (figures 3 and 4) while D.S. (not tested in experiment 1) showed almost no sharpening at 80% contrast (figure 4). The trends (and individual differences) shown in figure 4 were similar at each of the three test blurs (15, 30, 60 arcmin; not shown). The important result is that sharpening did not decrease at low contrasts.

4. DISCUSSION

The results show that briefly presented edges appear up to 40–50% sharper than those presented for longer durations. The size of this effect was similar to that observed in motion sharpening: at a speed of 16 deg s^{-1} , moving edges appeared 30–50% less blurred than slowly moving or stationary edges (Hammett *et al.* (1998), fig. 2). It seems likely, therefore, that the two phenomena have the same basis and that motion *per se* is not essential for sharpening.

One might wonder whether the effect of duration occurs indirectly, through a change in effective contrast. The effective contrast of a grating presented for 20 ms may be two to three times lower than one shown for 300 ms (Georgeson 1987). Thus our edges of 30% (or 90%) contrast may have had effective contrasts of 10–15% (or 30–45%) at 20 ms duration. Such a reduction is very unlikely to be a direct cause of the sharpening effect, however, since reducing contrast to as low as 8% does not change perceived edge blur (Georgeson 1994). Instead, it seems most likely that abrupt temporal changes (high temporal

frequency components) are the key factor in the effects of both motion and duration.

High-level models that specifically compensate for motion-induced blur appear to be ruled out by these findings. Similarly, the linear filter model of Pääkkönen & Morgan (2001) cannot explain these new results, for two reasons. First, their model specifically requires movement in order to produce sharpening and we have found that motion is not essential. Second, four out of the five test gratings in experiment 1 were pure sine waves. We found similar distortion for the sine waves (experiment 1) and the blurred square waves (experiments 1 and 2), but no linear model can predict distortion of sine waves.

The 'default' hypothesis (Burr & Morgan 1997) is less well specified, but the idea is that vision *assumes* the presence of those high spatial frequencies that might be present but undetectable at high speed: 'It is difficult to detect whether a moving stimulus is blurred or not; therefore it is reasonable that moving stimuli should all be seen as sharp' (Burr & Morgan 1997, p. 435). This interesting idea is unfortunately not consistent with experimental data. Motion makes blur discrimination harder only for small blurs up to about 5 arcmin (Pääkkönen & Morgan 1994; Burr & Morgan 1997), but it is just this range of blurs over which motion blurring (not sharpening) is seen (Hammett *et al.* 1998). Conversely, motion had little or no impact on blur discrimination at larger blurs (Burr & Morgan 1997), but it is the larger blurs (10–100 arcmin) that exhibit motion sharpening (Hammett *et al.* 1998). Thus the link between motion, blur discrimination and blur perception is just the opposite of that required by the 'default' hypothesis. Indeed, the original evidence (Burr 1980) that moving dots are 'seen as sharp' has turned out not to be generally true. Extensive motion smear is seen, except when that smear is masked or suppressed by other dots following behind (Chen *et al.* 1995). In addition, Hammett & Bex (1996) have shown that adapting to a missing fundamental square wave grating, which should reduce the detectability of sharp edges and so perhaps promote the default assumption of sharpness, actually reduces motion sharpening. This is further evidence against the 'default' hypothesis.

Findings similar to those of experiment 1 were reported by Galvin *et al.* (1999), using the method of adjustment with successive foveal presentation of single, high contrast, cumulative-Gaussian edges. The percentage change in blur matching with decreasing duration was very similar to our results, as shown in figure 3a. Galvin *et al.* (1999) have argued that sharpening is associated with conditions of 'poor visibility' and suggested that sharpness may be assumed when stimulus information is impoverished. This is essentially the default hypothesis of Burr & Morgan (1997) and so, for motion sharpening, it is contradicted by the evidence outlined in the previous paragraph. For the effects of duration, available data on blur discrimination are less comprehensive, but it appears that the effects of duration occur mainly for fairly sharp edges (below 5 arcmin; Burr & Morgan 1997) and for durations less than 150 ms (Westheimer 1991). Perceptual sharpening, however, is progressive across all durations below 500 ms (figure 3) and much the same for all levels of blur (figure 2). Thus, the default hypothesis is contradicted by

evidence from moving edges and moving dots, and has little positive support from the effects of brief presentation.

Of the four broad approaches considered here, the most promising seems to be early nonlinearity. We suppose that there is a contrast response nonlinearity that increases for 'fast' stimulation, i.e. at brief durations and high speeds of movement. This could arise if the visual response is a mixture of 'fast' nonlinear and 'slow' linear contributions, where the balance tips in favour of the nonlinear response that is the more sensitive in 'fast' conditions. Edge sharpening would occur when this mixed visual response was dominated by the response of the non-linear mechanism.

Our finding that sharpening is not diminished at lower contrasts has strong implications for the nature of the nonlinearity. It rejects our previous model in which a smooth, compressive nonlinearity distorts or 'clips' the peaks and troughs of the waveform (Hammett *et al.* 1998). On this model, distortion should decrease at lower contrasts, because the whole waveform now lies in a more nearly linear part of the transducer (an effect well known to engineers as 'small signal linearization'). Quantitative predictions were generated for various degrees of compressiveness by varying the semi-saturation parameter, S , in Hammett *et al.* (1998, eqn 5). Figure 4 illustrates how this model always predicts least sharpening at low contrasts, either when the compression is fairly severe ($S = 0.2$, typical of M cells in the retina and lateral geniculate nucleus (LGN); Kaplan *et al.* 1990; Sclar *et al.* 1990) or when it is mild ($S = 2$, typical of P cells in the retina and LGN). Experiment 2 showed no such reduction of the sharpening effect. In an extensive study of moving gratings, we have also found that motion sharpening is contrast invariant (M. A. Georgeson & S. T. Hammett, unpublished data). We must conclude that local compression of the spatial waveform by a static compressive nonlinearity cannot account for the sharpening phenomenon.

Physiological evidence for the compressive contrast response (of M cells) is not inconsistent with our rejection of it here as an account of sharpening. To induce a local distortion of the spatial waveform, the compression would have to come from a local transducer. The contrast gain control underlying the contrast response of M cells, however, is driven by signals from quite a wide retinal area and is not phase-sensitive; hence it is not localized (Benardete & Kaplan 1999). It can therefore scale down response amplitude at higher contrasts, as observed physiologically (e.g. Kaplan *et al.* 1990), without necessarily inducing spatial distortion. Moreover, the contrast gain control in M cells is effective mainly at low temporal frequencies. Both M and P cells show nearly linear contrast responses at high temporal frequencies (above *ca.* 10–15 Hz; Benardete *et al.* 1992; Benardete & Kaplan 1999), but this is where motion sharpening is greatest. Thus, the smooth compressive contrast response of retinal M-cells now appears to be a very unlikely basis for motion sharpening.

Our results (experiment 2) point instead to an *essential nonlinearity*—one that is *not* bypassed by low contrast signals. Such a nonlinearity could arise if increments and decrements (lighter and darker parts of the image) are carried by separate channels (ON- and OFF-centre receptive fields) with different gains. Previous work on the detection of flickering gratings has indeed suggested that contrast

gain may be greater for the OFF- than the ON-mechanism in the fast or transient channel (Kelly & Savoie 1978; Bergen & Wilson 1985). A possible physiological basis for this is the recent finding that in the primate LGN there were more OFF than ON cells in the M-cell layers (60% OFF, 40% ON) while these proportions were reversed in the P-cell layers (Levitt *et al.* 2001). The difference was highly significant ($\chi^2 = 8.82$, $p = 0.003$). Such a structural difference in cell densities could produce a difference between ON and OFF gains at the behavioural level. This difference would hold at all contrast levels and so could produce a waveform distortion that was contrast-invariant. It remains to be seen whether such a gain difference would lead to perceived sharpening, but preliminary observations of edges where this gain difference was simulated suggest that it does. A quantitative model incorporating gain difference, fast and slow temporal filtering and a model for blur encoding, is the next step forward.

In summary, we conclude that with brief presentations 'motion sharpening' can be observed on sine wave gratings and blurred edges, without motion, even at low contrast. This rules out several models that depend on motion *per se*. The preservation of the effect at low contrast also argues strongly against our previous model based on a static compressive local contrast transducer (Hammett *et al.* 1998). Nevertheless, the action of a different form of contrast response nonlinearity recruited by fast temporal changes remains a possible basis for this surprising distortion of spatial vision.

This work was supported by the Wellcome Trust (grant 056093). Experiment 1 was reported in preliminary form by Hammett & Georgeson (1998).

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