Motion deblurring in human vision

D. C. BURR[1] AND M. J. MORGAN[2]

[1] *Department of Psychology, University of Rome, Via dei Marsi 78, Rome and Isituto di neurofisiologia del CNR, Pisa, Italy*
[2] *Institute of Ophthalmology, University College London, Bath Street, London EC1V 9EL, UK*

SUMMARY

Under normal viewing conditions we are little conscious of blur in moving objects, despite the persistence of vision. Moving objects look more blurred in brief than in long exposures, suggesting an active mechanism for suppressing motion blur. To see whether blur suppression would improve visual discrimination of objects, we measured blur discrimination thresholds for moving Gaussian-blurred edges and bars. The observer's task was to decide which of two moving stimuli, presented successively, was the more blurred. It is known that for stationary objects the just-noticeable difference in blur increases with baseline blur; therefore, if motion increases blur, it would be expected to increase the just-noticeable difference in blur. An active deblurring mechanism, on the other hand, would be expected to counteract the detrimental effects of motion blur on discrimination performance. We found, however, that motion increased thresholds for blur discrimination, both for brief (40 ms) and for longer (150 ms) exposures. We conclude that motion deblurring is a subjective effect, which does not enhance visual discrimination performance. Moving objects appear sharp, not because of some special mechanism that removes blur, but because the visual system is unable to perform the discrimination necessary to decide whether the moving object is really sharp or not.

1. INTRODUCTION

The fact that luminous objects moving in the dark seem to leave behind them a long tail was commented on by Leonardo da Vinci (MacCurdy 1956) and later by Newton (1730). The effect, sometimes referred to as 'visible persistence', is exploited in firework displays. Cartoonists regularly employ persisting images of objects to indicate movement. In normal daytime vision, however, we are little conscious of persisting trails behind moving objects. Much of the difference between firework displays and normal daytime vision probably results from the extremely high contrasts of bright images on the dark-adapted retina, and the absence of visual patterns that would normally mask the streak. There is also a difference in time constants between rods and cones, and the time constants of both increase at low levels of illumination (e.g. Schnapf *et al.* 1990).

The integration time for detecting moving objects under normal photopic levels of illumination has been shown to be in the region of 120 ms (Burr 1981), equivalent to a 1/8 second shutter speed, and it is clear that we do not see moving objects smeared out over such a long time interval. Counter-intuitively, however, if a moving dot is displayed only briefly it leaves behind a subjectively larger tail when it moves for a longer period. Figure 1 (reproduced from Burr (1980)) illustrates this result. Observers were required to match the length of a short stationary line to the length of the apparent streak left by an array of moving dots. For four different dot speeds the dots left the longest streak at exposure durations of around 40 ms, while at the longer durations there was virtually no streak. Similarly, moving dots appear to persist for longer when they move in tight circles than along straight lines or shallow arcs (Burr 1979), or when they frequently change their direction (Watamaniuk 1991). All these findings argue that there is a mechanism that suppresses the subjective persistence of objects once their direction of motion has been identified.

In computer vision, photographs of objects that have been blurred by fast movement can be enhanced by deconvolution with the impulse response corresponding to the temporal profile of the camera shutter (Gonzalez & Wintz 1977). Deconvolution cannot restore high spatial frequencies that have been removed by blurring, but it can boost those that have been attenuated. Motion deblurring in human vision could work in a similar way, perhaps by increasing the gain of high spatial frequency mechanisms relative to low. An alternative strategy would be to filter out signals from the mechanisms with the longer time constants. In neither case would there be a real improvement in the resolution of moving targets. Increasing the gain of high spatial frequency mechanisms will increase the amplitude of noise as well. Filtering out the neurones with longer time constants will remove the very mechanisms responsible for perception of fine detail. It thus seems unlikely that the subjective removal of motion blur will be accompanied by a real improvement in spatial resolution for moving targets.

Anderson & van Essen (1987), however, have argued for a mechanism of motion deblurring that implies a real gain in resolution. They propose an internal neural 'shifter circuit' that tracks the moving

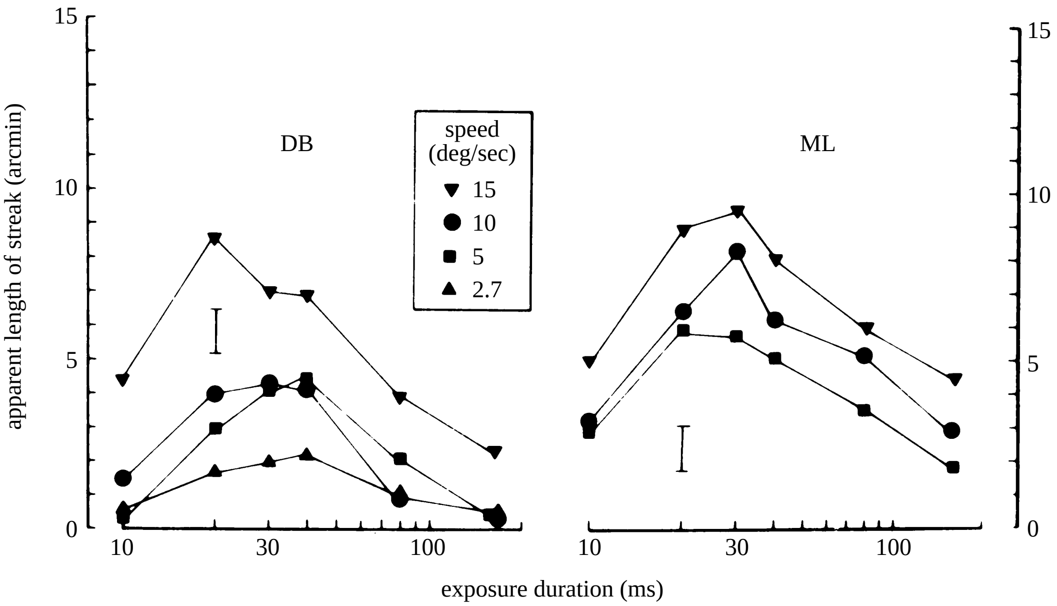

Figure 1. The apparent length of the motion streak of dots moving along a constant linear trajectory, as a function of exposure duration, for various image speeds (reproduced with permission from Burr 1980).

object through space in a retinotopic framework. As evidence for such a mechanism they cited the well established finding that vernier hyperacuity of 5 arcsec can be obtained with targets moving at up to 5 deg s^{-1} (Westheimer & McKee 1975). However, vernier acuity for briefly presented targets may not be limited by high spatial frequency resolution in the first place, so it is not clear that a decrement in performance from motion blur would be expected. In longer exposures (1 s), where even higher acuities are obtained, motion does cause a deterioration in performance (Morgan *et al.* 1983). Moreover, a different kind of hyperacuity task (spatial interval discrimination), which probably does depend upon high spatial resolution, does show a performance decrement due to motion, even in brief exposures (Morgan & Benton 1989). Recent experiments show that the limit on moving hyperacuity for gratings is not velocity at all, but temporal frequency, both for stereo (Morgan & Castet 1995) and for vernier (Levi 1996). For sufficiently low frequency gratings (0.04 cyc deg^{-1}) vernier acuity is not degraded by speeds up to 1000 deg s^{-1}.

In a different attack on the problem, Pääkkönen & Morgan (1993) measured blur discrimination for moving edges. Blur discrimination for stationary targets shows a characteristic dependence on the baseline level of blur. If the observer's task is to distinguish between two targets, one with the baseline blur, b, and the other with blur $b+\delta b$, the threshold δb does not increase monotonically with b but follows a 'dipper function'. It is minimal at a small but finite level of b, and increases as a power function of b thereafter (Watt & Morgan 1983). This suggests a simple strategy for measuring the equivalent blur due to motion. Pääkkönen and Morgan found that blur discrimination thresholds were raised by motion, as was the minimum in the dipper function. The data were accounted for by a simple model in which motion added an equivalent blur that scaled directly with velocity.

However, Pääkkönen and Morgan used only a single exposure duration (250 ms). According to the findings of Burr, we would expect to measure an even greater amount of equivalent blur from motion at an exposure duration (40 ms), too short for deblurring to occur (Burr 1980; see figure 1). This was the reasoning behind the experiment that we report here. We compared blur discrimination for stationary and moving edges and bars at two different exposure durations, 40 and 150 ms.

2. METHODS

(*a*) *Apparatus*

The stimuli were generated on a Cambridge Research Systems VSG 2/3 graphics processor and presented on a Barco Calibrator II visual display. Observations were carried out in a dimly lit room. The CIE coordinates of the achromatic mean luminance screen were: $x = 12.5$ cd m^{-2}, $y = 0.358$, $z = 0.349$. The frame rate was 150 Hz and one pixel subtended a horizontal visual angle of 0.43 arcmin.

(*b*) *Subjects*

The subjects were the two authors (M.J.M. and D.C.B.), both with corrected 6/6 vision.

(*c*) *Stimuli*

The display was viewed at a distance of 200 cm at which the active area of the screen subtended a visual angle of 11° × 7°. The horizontally moving edges or bars were vertically oriented and their vertical profile was constant. The horizontal luminance profile of the edges ($E(x)$) and the bars ($B(x)$) were defined by

$$E(x) = L_0\left\{1+c\left[\frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} \mathrm{e}^{(-k^2/2\sigma^2)}\mathrm{d}k-0.5\right]\right\} \qquad (1)$$

$$B(x) = L_0(1+c\,\mathrm{e}^{-x^2/2\sigma^2}), \qquad (2)$$

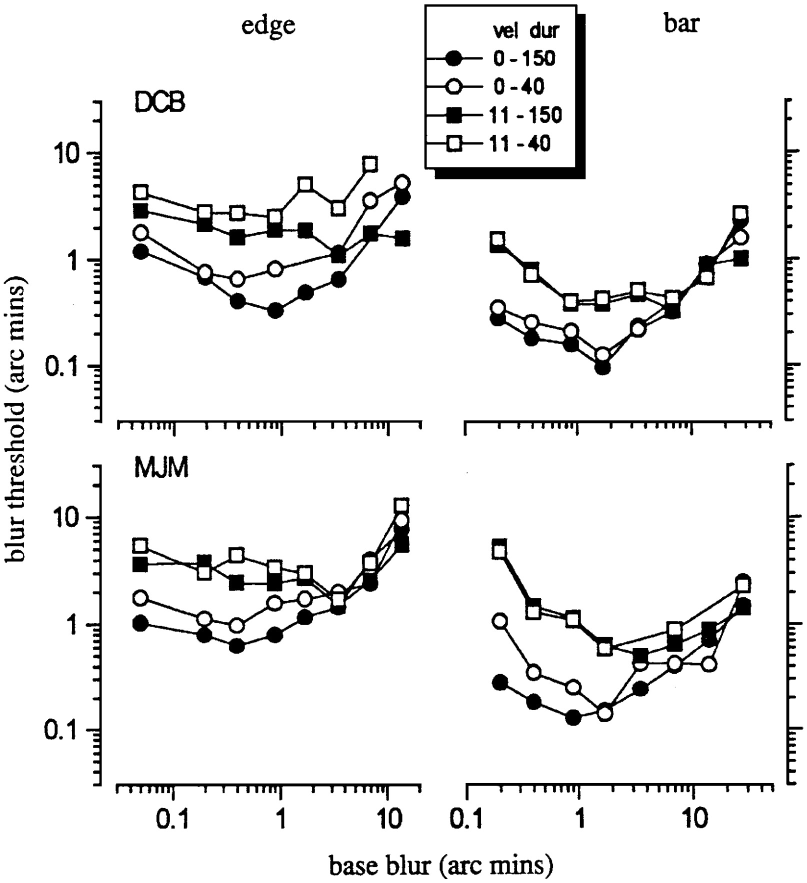

Figure 2. Blur discrimination thresholds (δb) as a function of base-blur b, for edge profiles on the left (derived from equation (1)) and line profiles on the right (equation (2)). Circles refer to stationary patterns, squares to patterns moving at 11 deg s^{-1}; open symbols to brief presentations (40 ms), filled symbols to longer presentations (150 ms). See table 1 for statistical analysis of the results. Each estimate of threshold was based on at least three separate determinations (QUESTs) per measure. From these we obtained a standard error of the geometric mean (i.e. standard error of log blur thresholds).The average s.e. for figure 2 was 0.083 log-units (D.C.B.) and 0.087 (M.J.M.). For figure 3 D.C.B. = 0.090 and M.J.M. = 0.088. These values are smaller than the symbol size (0.13 log-units) in the figures. Also, no error was greater than 0.18 log-units.

where x is horizontal distance, σ is the standard deviation of the Gaussian blurring function, L_0 is the mean luminance, and c is the Michelson contrast, defined as

$c = (L_{\max} - L_{\min})/2L_0$.

The frame rate of the display was 150 Hz, with 1000 lines of horizontal resolution. Movement was produced by updating the horizontal position of the stimulus every frame.

(*d*) *Procedure*

On each trial the observer was presented with two stimuli in succession, separated by a 500 ms interval at which the screen was at mean luminance. One interval contained the baseline stimulus with $\sigma = b$ and the other the comparison stimulus with $\sigma = b + \delta b$. The stimulus appeared abruptly at a position $c \pm (w/2)$ on the screen, where c was the centre and w the amplitude of the motion trajectory. The direction of motion was random over trials. The observer selected the appropriate one of two switches to indicate the interval in which the stimulus was more blurred and the response was recorded. For each baseline blur, two conditions of exposure duration (40 versus 150 ms) and two conditions of velocity (0 versus 11 deg s^{-1}) were pseudo-randomly interleaved. Thresholds were determined by a QUEST procedure (Watson & Pelli 1983), which adaptively homes in on threshold and places the next value of δb near that value. The final estimate of threshold was obtained by fitting cumulative Gaussian psychometric functions to all the pooled data of a particular condition (at least 150 trials). Thresholds were defined as the 75% points on the function.

3. RESULTS

Figure 2 shows blur discrimination thresholds, for edges of 5% contrast and bars of 95% contrast, as a function of the base blur. For all stimuli thresholds increased at higher blur levels. For smaller baseline blurs, thresholds for edges showed little change, but bars showed a 'dipper' function with an optimum, non-zero level of blur. The 'dip' was more pronounced for bars than for edge patterns. An analysis of variance was carried out with blur, velocity, exposure and subjects as factors (table 1). The effect of blur was significant both for bars ($p = 0.002$) and for edges ($p < 0.001$). The effect of velocity was also significant for both kinds of stimulus (bars: $p = 0.048$; edges, $p < 0.001$).

The results also show a tendency for blur thresholds to be larger for brief than for long exposures, for both edges as for bars. The tendency was small (a factor of 1.2 on average), but highly significant ($p < 0.001$) in

Table 1. *Analysis of variance*

source	sumsq	d.f.	meansq	F-ratio	p
a moving bars					
VEL	3.744	1	3.744	4.23	0.048
EXPO	0.260	1	0.260	0.294	0.592
SUBJ	0.922	1	0.922	1.041	0.315
B*V	7.404	7	1.058	1.195	0.335
B*E	0.578	7	0.083	0.093	0.998
V*E	0.011	1	0.011	0.012	0.914
B*V*E	1.092	7	0.156	0.176	0.988
ERROR	27.437	31	0.885		
b moving edges					
VEL	40.43	1	40.43	26.073	< 0.001
EXPO	29.363	1	29.363	18.934	< 0.001
SUBJ	11.097	1	11.097	7.156	0.012
B*V	9.157	7	1.308	0.844	0.56
B*E	21.02	7	3.003	1.936	0.097
V*E	8.963	1	8.963	5.779	0.022
B*V*E	10.903	7	1.558	1.004	0.447
ERROR	48.075	31	1.551		

the case of edges. In the case of bars the effect was non-significant ($p = 0.592$). The difference between thresholds for brief and long presentations occurred for both moving and stationary stimuli, by about the same amount. There was no evidence from these data that motion had a more detrimental effect at short than at long exposures. Rather, motion and brief exposure both increased discrimination thresholds, seemingly independently. This is supported by the lack of significant interactions between the main variables in the analysis of variance. The only interaction to reach significance was between velocity and exposure in the case of edge stimuli ($p = 0.022$). The probable interpretation from this (see figure 2) is that duration had smaller effects with moving stimuli than with stationary, particularly for observer M.J.M. The same effect is seen for bars, but the interaction was non-significant ($p = 0.914$).

Figure 3 shows blur discriminations as a function of contrast of the stimulus for the edge condition, with base blur 0 (hard edge). Blur discrimination improved with increasing contrast, following a roughly square-root law (log–log slope of -0.5) for M.J.M. as previously reported (Watt & Morgan 1983), but at a much shallower rate for observer D.C.B. It is unclear to us why the results should be different for the two observers. However, the effect of image motion and duration was essentially the same at all contrasts: motion increased thresholds by about a factor of three, while exposure duration affected thresholds by less than a factor of 1.5.

In summary, movement increased blur discrimination thresholds, and there was no evidence that this deleterious effect of movement was greater for briefly exposed stimuli. Brief exposure also raised thresholds, but if anything, this effect was more pronounced for stationary than for moving stimuli.

4. DISCUSSION

The results confirm previous evidence that mechanisms involved with processing moving stimuli (both bars and edges) have a higher level of intrinsic blur than those for stationary stimuli. They further show a small but consistent dependence on exposure duration for both stationary and moving stimuli. Several reasons may explain this effect. One could be the lower effective contrast of the brief stimuli. As the visual system integrates contrast of both stationary and moving stimuli over about 120 ms (Burr 1981), a stimulus of 40 ms will have only one-third the effective contrast of the longer stimulus (verified by the three-fold differences in detection threshold in figure 3). As blur discrimination depends on contrast, usually with a square-root dependency (previous data and for M.J.M. in this paper), the three-fold reduction in effective contrast should result in a root-three reduction in threshold, more than sufficient to explain the current results. Alternatively, as the brief stimulus is truncated in time it has a wider range of temporal frequencies in its spectrum than the longer stimuli, and will excite more transient mechanisms even when stationary. This may reduce blur resolution. However, as the effect reported here is so small, and easily accounted for by reduced temporal integration, it would seem to be unnecessary to indulge in this sort of speculation.

What the results most clearly show is that exposure duration affects blur discrimination in a quite different way than it affects blur appearance. Figure 1 shows that at 10 deg s^{-1}, the apparent length of the smear of a

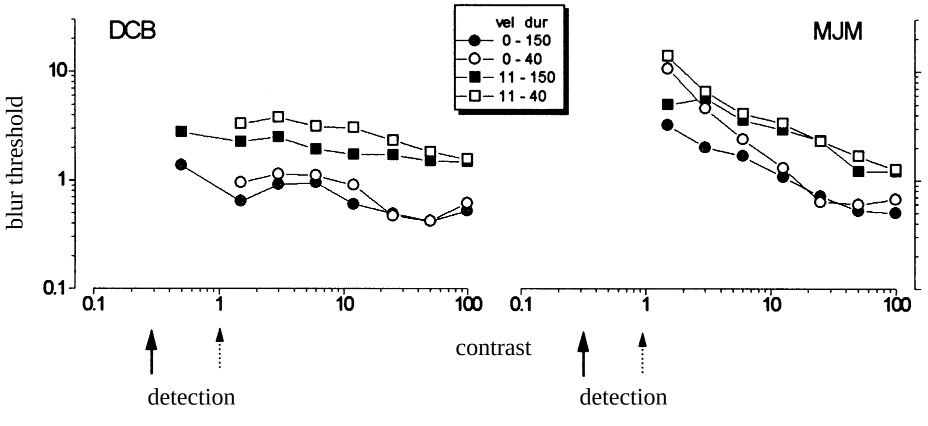

Figure 3. Thresholds for discrimination of blur in edge profiles (δb against a base blur of 0), as a function of stimulus contrast. Symbols as for figure 2.

moving dot decreases from 4 min at 40 ms exposure to less than 1 min at 150 ms (for DB), and from 9 to 3 min for ML; yet the difference in blur discrimination reported here was less than a factor of 1.5 over the same range, and not confined to the motion condition. This suggests that the appearance of blur is determined by processes other than those that determine blur discrimination, and is not strictly related to the intrinsic blur in the system (for the concept of intrinsic blur see Watt & Hess (1987)).

Possible physical differences between the display used by Burr and the one in the present experiment should be considered. The single dots used by Burr were more spatially localized and had less overall energy than the bars and dots in our experiment. However, subjective motion deblurring has been observed using multiple dots (Watamaniuk 1991) and moving gratings (Hammett & Bex 1996). Moreover, we observed informally the same effect reported by Burr: briefly exposed moving bars and edges appeared more blurred than those exposed for longer.

Image motion necessarily results in an attenuation of high spatial frequencies, and this should be accompanied by an increase in intrinsic blur. This explains why we are poorer at blur discrimination, and why the intrinsic blur increases with image motion (see Pääkkönen & Morgan (1993) for a detailed model of why this occurs). However, there is no *a priori* reason why this should determine the appearance of the edge or the length of the streak of a moving dot. It is not the resolution of the filters that dictates appearance. For example, spatial resolution is greatly reduced at low luminance levels. This probably results in an increase in estimates of intrinsic blur. However, stationary objects do not appear more blurred with dim lighting than in normal conditions. In order to perceive an object as blurred, we must be able to detect the blur, and for that we require good spatial resolution. If that spatial resolution is not there, we are unable to detect sharpness, but equally unable to detect blurredness. So if we are unable to resolve the spatial frequencies that allow us to discriminate between sharp and blurred, both will be indistinguishable, but how will they appear? It seems reasonable to assume that under these circumstances we see images to be sharp, and there is some evidence that this occurs (Anderson 1983).

The question remains as to why briefly exposed moving dots do appear to be smeared. It was initially suggested that moving dots may excite two classes of mechanisms, those specialized for motion and those for static vision (Burr 1979). The motion mechanisms will perceive the motion and, for the reasons outlined above and elsewhere (e.g. Burr *et al*. 1986), should not signal blur. However, the non-motion mechanisms will simply integrate all contrast energy over time, and signal the integrated visual streak caused by motion. Now the motion signal necessarily requires time to build up, far longer than the signal for a stationary image. This is because a brief signal not only has reduced motion energy in the veridical direction, but it has additional energy in the opposite direction, caused by the increased spread of temporal frequencies. Any motion detector with an opponent stage (as all essentially do) will produce a very weak signal to this type of stimulus (Derrington & Goddard 1989; Morgan & Cleary 1992).

Thus the contribution of the motion response relative to the non-motion response will rapidly increase with time. If signals from motion detectors are comparatively 'blur-free', then apparent blur should decrease with exposure duration, as observed. Additional mechanisms, such as mutual inhibition between motion and non-motion units or other nonlinearities, may enhance this effect further.

Whatever the actual mechanism by which the spatial signal from motion mechanisms is used to code visual appearance, the results of this study show that the appearance of what we see is determined by processes quite distinct from those that determine our ability to discriminate blur. This and previous studies show that there is no need for complicated devices such as shifter circuits for this to occur: it is a simple property of the poor spatial resolution of detectors designed to respond to moving stimuli. 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. In the same way, people who gradually lose high spatial frequencies from their vision because of a slowly developing refractive error are not aware of subjective blur, until a performance task like reading brings their deficit forcefully to their attention.

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REFERENCES

Anderson, C. H. & van Essen, D. C. 1987 Shifter circuits: a computational strategy for dynamic aspects of visual processing. *Proc. natn. Acad. Sci. USA* **84**, 6297–6301.

Anderson, S. J. 1993 Visual processing delays alter the perceived spatial form of moving gratings. *Vision Res.* **33**, 2733–2746.

Burr, D. C. 1979 On seeing objects in motion. Unpublished PhD thesis, University of Cambridge.

Burr, D. C. 1980 Motion smear. *Nature, Lond.* **284**, 164–165.

Burr, D. C. 1981 Temporal summation of moving images by the human visual system. *Proc. R. Soc. Lond.* B **211**, 321–339.

Burr, D. C., Ross, J. & Morrone, M. C. 1986 Seeing objects in motion. *Proc. R. Soc. Lond.* B **227**, 249–265.

Derrington, A. M. & Goddard, P. A. 1989 Failure of motion discrimination at high contrasts: evidence for saturation. *Vision Res.* **29**, 1767–1776.

Gonzalez, R. C. & Wintz, P. 1977 *Digital image processing*. Reading, MA: Addison-Wesley, p. 4.

Hammett, S. T. & Bex, P. J. 1996 Motion sharpening—evidence for the addition of high spatial frequencies to the effective neural image. *Vision Res.* **36**, 2729–2733.

Levi, D. M. 1996 Pattern perception at high velocities. *Current Biol.* **6**, 1020–1024.

MacCurdy, E. 1956 *The notebooks of Leonardo da Vinci*. London: Jonathan Cape (2nd edition 1977), p. 230.

Morgan, M. J. & Benton, S. 1989 Motion deblurring in human vision. *Nature, Lond.* **340**, 385–386.

Morgan, M. J. & Castet, E. C. 1995 Stereoscopic depth perception at high velocities. *Nature, Lond.* **378**, 380–383.

Morgan, M. J. & Cleary 1992 Ambiguous motion in a two-frame sequence. *Vision Res.* **32**, 2195–2198.

Morgan, M. J., Watt, R. J. & McKee, S. P. 1983 Exposure duration affects the sensitivity of vernier acuity to target motion. *Vision Res.* **23**, 541–546.

Newton, Sir Isaac 1730 *Opticks*. USA: Dover Publications (1952).

Pääkkönen, A. & Morgan, M. J. 1993 The effects of motion blur on blur discrimination. *J. Opt. Soc. Am.* A **11**, 992–1002.

Schnapf, J. L., Nunn, B. J., Meister, M. & Baylor, D. A. 1990 Visual transduction in cones of the monkey macaca-fascicularis. *J. Physiol., Lond.* **427**, 681–713.

Watamaniuk, S. N. J. 1991 Motion trajectory networks reduce visual persistence. *Invest. Ophthal., Vis. Sci.* **32**, 825.

Watson, A. B. & Pelli, D. G. 1983 QUEST: a Bayesian adaptive psychometric method. *Percept. Psychophys.* **33**, 113–120.

Watt, R. J. & Hess, R. F. 1987 Spatial information and uncertainty in anisometropic amblyopia. *Vision Res.* **27**, 661–674.

Watt, R. J. & Morgan, M. J. 1983 The recognition and representation of edge blur: evidence for spatial primitives in human vision. *Vision Res.* **23**, 1465–1477.

Westheimer, G. & McKee, S. P. 1975 Visual acuity in the presence of retinal-image motion. *J. Opt. Soc. Am.* **65**, 847–851.

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