No role for motion blur in either motion detection or motion-based image segmentation

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Received April 24, 1997; accepted September 8, 1997

The human contrast sensitivity function is bandpass in form for stimuli of low temporal frequency but low pass for flickering or moving stimuli. Because the loss in sensitivity to moving stimuli is large, images moving on the retina have little perceptible high-spatial-frequency content. The loss of high-spatial-frequency content—often referred to as motion blur—provides a potential cue to motion. The amount of motion blur is a function of stimulus velocity but is significant at velocities encountered by the visual system in everyday situations. Our experiments determined the influence of high-spatial-frequency losses induced by motion of this order on motion detection and on motion-based image segmentation. Motion detection and motion-based segmentation tasks were performed with either spectrally low-pass or spectrally broadband stimuli. Performance on these tasks was compared with a condition having no motion but in which form differences mimicked the perceptual loss of high spatial frequencies produced by motion. This allowed the relative salience of motion and motion-induced blur to be determined. Neither image segmentation nor motion detection was sensitive to the high-spatial-frequency content of the stimuli. Thus the change in perceptual form produced in moving stimuli is not normally used as a cue either for motion detection or for motion-based segmentation in ordinary situations. [S0740-3232(98)02402-8]

OCIS codes: 330.4150, 330.1800, 330.5000.

I. INTRODUCTION

In most situations there are several ways to perform a given perceptual task. The world provides many visual cues that may be used alone or in combination according to the demands of the task and the quality of the stimulus. In image segmentation, for example, orientation, texture, chromaticity, and motion have been shown to be effective cues that allow observers to discriminate objects from their background.

Although at least three different motion cues have been recognized—real motion, motion of texture-contrast modulations, and moving features[1]—we shall be concerned only with real motion (sometimes called first-order or Fourier motion); with real motion there is stimulus energy at the spatial and temporal frequencies of the moving stimulus. This cue can, however, be further broken down into the motion itself and perceptual characteristics that change as a result of the motion. One such indirect cue is the profound loss in high-spatial-frequency content associated with stimuli moving on the retina, frequently termed motion blur. Since many of the stimuli commonly used to explore motion are spectrally broadband and most natural scenes contain both low- and high-spatial-frequency information,[2] the perceived loss of high spatial frequencies might be used as an additional cue in motion perception.

A. Contrast Sensitivity

The eye is not equally sensitive to contrast variations at all spatial and temporal frequencies; rather, the contrast sensitivity function (CSF) is bandpass for stimuli of low temporal frequency but low pass with large high-spatial-frequency losses for briefly presented or rapidly flickering stimuli and for stimuli moving on the retina.[3–9] This implies that low-contrast regions of the visual field moving over the retina are accompanied by the perceptual loss of high spatial frequencies.

The perceptual loss of high spatial frequencies is very large. For example, a sinusoidal grating of 5 cycles per degree (c/deg) moving at a constant velocity of only 4.6 deg/s—the velocity of all the moving stimuli employed in this study—requires more than 2.1 log units of the contrast needed to detect a static grating of the same spatial frequency.[3] The effect is even more pronounced at higher spatial frequencies—detailed treatments of the motion-induced perceptual spatial low-pass filtering are available.[10,11] Threshold elevation as a function of stimulus velocity is shown in Fig. 1.

B. Window of Visibility

Watson *et al.*[12,13] introduced the "window of visibility" to illustrate the conditions under which time-sampled and continuous motions are indistinguishable (but see also Fahle and Poggio[14] as well as Pearson[15]). Here we use a window of visibility to illustrate that, for any system with limited *temporal* bandwidth, the temporal limit implies the loss of high *spatial* frequencies—motion blur—in moving stimuli, irrespective of the exact shape of the passband characteristics of the system.

The window partitions the spatial-frequency–temporal-frequency plane into two regions: a central region, the window, containing combinations of low spatial and low temporal frequency that, under certain circumstances, might be visible to an observer, and a surrounding region containing combinations of high spatial and high temporal frequency that are always invisible.

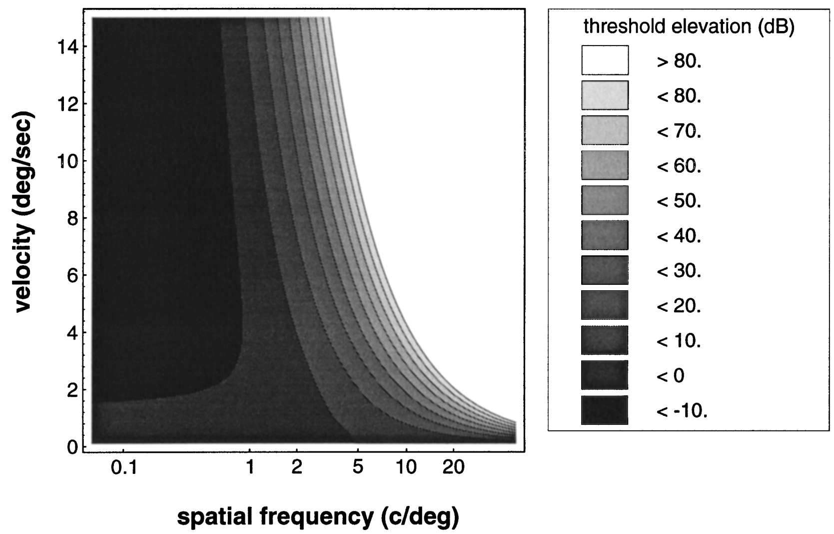


Fig. 1. Threshold elevation relative to static sensitivity shown as a density plot at each spatial frequency (x axis) as a function of velocity (y axis); threshold elevation is expressed in decibels (data adapted from Kelly[3]).

The shape and the size of the window of visibility varies according to stimulus contrast. There is a family of windows of visibility with boundaries that indicate combinations of spatial frequency, temporal frequency, and contrast outside which no stimulus with lower contrast is visible although stimuli of higher contrast might be. These boundaries correspond to Koenderink and van Doorn's isosensitivity contours.[16]

Figure 2 shows two schematic windows of visibility: the white polygon shows combinations of spatial and temporal frequencies that are visible for stimuli of low contrast, and the dashed rectangle indicates the maximal extent of the window of visibility for stimuli of very high contrast.

The significance of the window of visibility for our experiments is also illustrated in Fig. 2. One of our stimuli contained only low spatial frequencies (the low-pass stimulus), one contained only high-frequency components (the high-pass stimulus), and one (the broadband stimulus) was the sum of the low- and high-pass stimuli. The spectral energy of low- and high-pass stimuli when static and when in motion is shown in Fig. 2. Low-pass stimuli are shown as thick bars passing through the origin (zero temporal and zero spatial frequency) at the center of the window of visibility. Low-pass stimuli almost always fall within the low-contrast window of visibility and thus are visible whether static (horizontal bar) or moving (diagonal bar). On the other hand, high-pass stimuli, isolated thick bars in the first and third quadrants, are visible when static but become invisible when moving. This illustrates the effective loss of high-frequency information produced by motion.

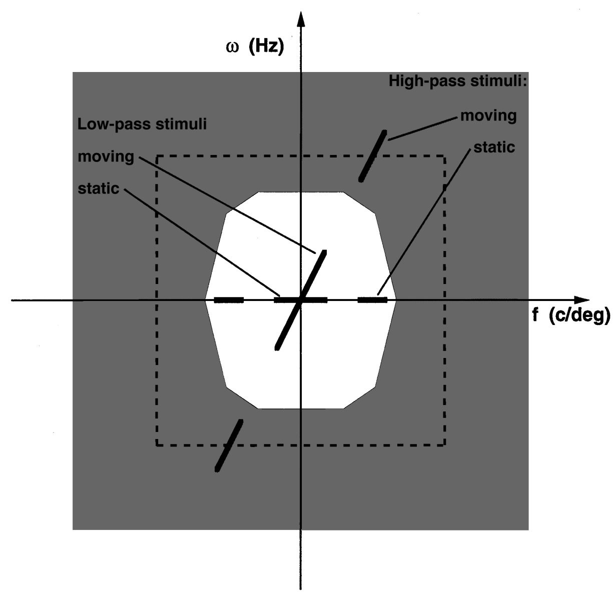


Fig. 2. Window of visibility for low-contrast stimuli. The gray region indicates combinations of spatial and temporal frequency that, at low contrasts, are invisible to the human observer. The dashed lines illustrate the extent of a window of visibility for stimuli of very high contrast. Static stimuli are shown as horizontal bars: low-pass static stimuli near the origin and high-frequency static stimuli as isolated horizontal bars away from the origin. Stimuli moving at a constant speed are shown as diagonal bars: low-pass moving stimuli near the origin and high-frequency moving stimuli as isolated diagonal bars in the first and third quadrants.

C. Motion Blur and Eye Movements

Motion blur often goes unnoticed. This is because we track interesting moving objects with our eyes and thus effectively reduce their motion on the retina while at the same time increasing the speed, and reducing the effective contrast, of the less interesting background.[17–21]

Since smooth-pursuit eye movements require some time to begin, however, the loss of high-spatial-frequency content is present early in the time course of motion detection and image segmentation; thus it could help in detecting motion or in supporting motion-based image segmentation even though, during ordinary life, it often goes unnoticed.

D. Experiments

To determine whether the human visual system uses motion blur as a cue in motion perception, we compared its effectiveness with that of a standard motion cue.

The stimuli consisted of small circular regions (DOTs) that were either spatially lowpass (LP-DOTs) or broadband (BB-DOTs); see Figs. 3–5 below for examples. The BB-DOTs were created by adding a high-pass stimulus (HP-DOT) to the LP-DOTs. A preliminary two-alternative forced-choice discrimination experiment confirmed that HP-DOTs were visible when static but invisible when moving at the speed that we used.

The difference in spatial-frequency content between LP- and BB-DOTs was designed to mimic the perceptual spatial-frequency difference produced by motion so that the perceptual difference between static BB-DOTs and static LP-DOTs would match the perceptual form difference between static and moving BB-DOTs.

Two experiments were performed: a motion detection experiment and a motion-based image segmentation experiment. In the detection experiment the observers were required merely to indicate which interval contained the moving target, and in the motion-based image segmentation experiment observers were required to discriminate between two differently shaped moving targets.

The moving-target stimuli in both experiments were either LP- or BB-DOTs. Both types provide the visual system with motion energy, but only the BB-DOTs suffer the perceptual loss of high spatial frequencies when moving. As a control, another experimental condition with static LP-DOTs embedded in static BB-DOTs was performed. In this condition the loss of high-spatial-frequency content is the only cue.

The background always contained only static DOTs, which, except in the static control, were of the same type as that of the moving targets.

2. GENERAL METHOD

The display consisted of an irregular array of DOTs. The target was always a set of six adjacent DOTs with temporal or spatial characteristics that differentiated them from the static background.

To generate the stimuli, the 1280×1024-pixel screen was first divided into an imaginary grid of 96×96-pixel squares; the origin of the grid was randomized over observation intervals, and a single DOT (24-pixel radius) was nominally centered on each intersection of the grid. Second, the horizontal and vertical displacement of each DOT relative to its nominal grid location was randomized uniformly between -23 and $+24$. The random perturbation of DOT location was chosen such that no two DOTs overlapped and such that the DOT density was, on average, equal everywhere on the screen.

A. Target Stimuli

The targets were a subset of six DOTs in adjacent rows and columns defined either by common motion or by common form. The target matrix could appear anywhere on the screen, and its position was randomly and independently chosen on each presentation. The six DOTs of the target matrix formed a roughly rectangular pattern whose longer axis was horizontally oriented as illustrated in Fig. 3 for the static condition. The background DOTs of Fig. 3 are BB-DOTs and are, as always, static; the target consists, in this case, of six static LP-DOTs.

In the detection tasks the subjects had to indicate which of two temporal intervals contained the target matrix. In the image segmentation experiments, the subjects were presented with a horizontally oriented matrix (target) in one observation interval and a vertically oriented matrix in the other and had to indicate the interval in which the horizontally oriented matrix had appeared.

B. Motion

The motion of each DOT in a target matrix is described parametrically as a function of time t (in seconds) by

$$x(t) = r \sin(147.2t + \phi), \quad (1)$$

where $x(t)$ is the horizontal position at time t relative to the starting position, and by

$$y(t) = \rho r \cos(147.2t + \phi), \quad (2)$$

where $y(t)$ is the vertical position at time t relative to the starting position; r is the spatial amplitude of oscillation (set to 4 pixels); ϕ is a random variable uniformly distributed over $[-\pi, \pi]$, which served to randomize the starting position; and ρ is a binary random variable that was either $+1$ or -1 and was used to randomize the direction of motion.

The net result of the motion described by Eqs. (1) and (2) is that the centers and every point in every DOT was translated along a circular path whose radius was equal to r. This is shown in Fig. 4.

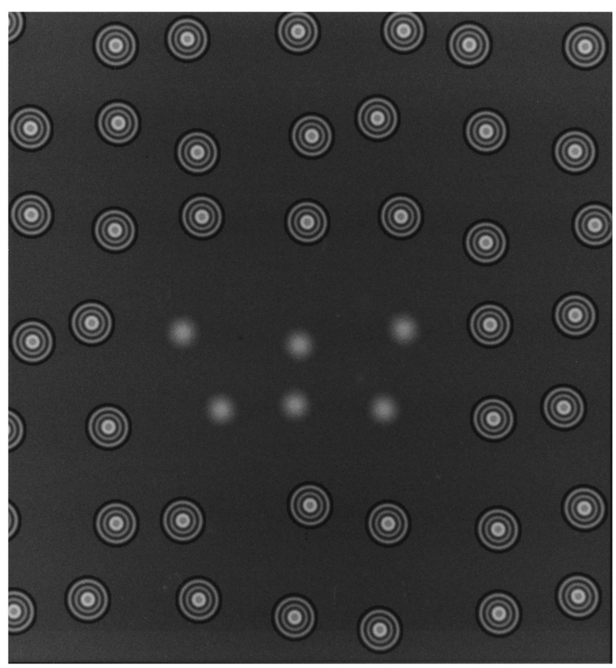


Fig. 3. Screen shot of a region of the screen with the DOTs used for segmentation based on form rather than motion; the target matrix comprised six LP-DOTs—the blurred elements in the center of the image—to be detected against a background of BB-DOTs.

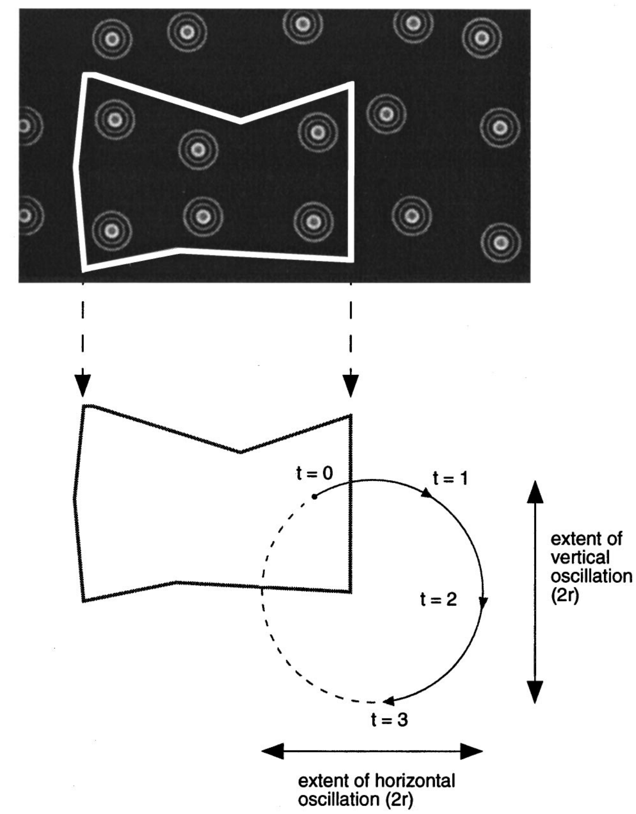


Fig. 4. Schematic illustration of target motion. The roughly rectangular target matrix containing six DOTs translated around a circular path over time; the radius of the circular path was equal to the spatial amplitude of oscillation r in Eqs. (1) and (2). Note that, first, for clarity, the radius is grossly enlarged. During the experiments it was 4 pixels (for comparison, the DOT diameter was 48 pixels). Second, the frame of reference was invisible and is added for illustration purposes only.

The period of this idealized circular path would be 42.7 ms; the linear velocity of the motion was constant at 4.6 deg/s.

The reason for choosing a velocity between 4 and 5 deg/s was twofold. First, human motion perception is very good at such velocities and, subjectively, is accompanied by a strong sense of motion. Second, it is representative of motion that the visual system encounters in everyday situations—a stimulus velocity of 4.6 deg/s corresponds to objects moving at approximately 3 km/hr at a 10-m distance (e.g., a person walking past the observer) or at 50 km/hr 150 m away (e.g., a car or a train).

Although Eqs. (1) and (2) express the displacement of the targets in the horizontal and vertical directions, it should be noted that, at any given time during the experiment, the stimuli were equally likely to be moving in any direction. This ensured that, if high-spatial-frequency losses were a potential cue to motion, this information was equally available to all directionally tuned detectors.[22,23] Note also that, because of the sampling rate of the display (60 Hz), the motion is not truly circular: the average number of samples in each cycle of the "circle" was in fact only 2.56. However, the motion regime does satisfy the following necessary and sufficient conditions:

1. At any moment the direction of motion of a DOT around the circle must be unambiguous (more than 2 samples per cycle). This facilitated perceptual grouping of the target DOTs, thus ensuring that when motion was seen, it was seen as coherent.

2. The distribution of motion vectors must be isotropic, so that the same information is available in all directional detectors. This was accomplished by randomizing the starting phase ϕ between observation intervals and between trials and also by ensuring that the coefficient of t in Eqs. (1) and (2) was not divisible by 2π. This meant that, on each observation interval, successive cycles were always sampled at different points on the circle.

As long as we respected these constraints, all observers reported a strong sense of coherent motion, which, for presentation times as short as 100–150 ms, appeared to be smooth circular motion. However, none of our conclusions depend on the assumption that the motion was actually circular.

C. Temporal Characteristics of the Stimuli

The temporal envelope of the signal was a rectangular function of time, i.e., the maximum contrast was present throughout each observation interval.

To avoid problems associated with visual aftereffects, random noise with the same mean luminance as that of the background was displayed on the entire screen during the interstimulus interval and after each trial.

D. Spatial Characteristics of the Stimuli

All DOTs had a radius of 24 pixels and were chosen to be circularly symmetric in order to have identical spectral-energy content in all directions. DOTs with three different spatial-frequency characteristics were used.

1. *Low-pass DOTs.* LP-DOTs were constructed to contain no detectable energy at high spatial frequencies. They were the impulse response of an ideal, circularly symmetric low-pass filter with a nominal cutoff frequency of 2 c/deg, weighted by a Hanning window:

$$\text{LP-DOT}(x, y) = \begin{cases} [\frac{1}{2} + \frac{1}{2}\cos(\sqrt{x^2 + y^2})] \dfrac{\sin(\frac{3}{4}\sqrt{x^2 + y^2})}{\frac{3}{4}\sqrt{x^2 + y^2}} & \text{if } \sqrt{x^2 + y^2} \leqslant \pi \\ 0 & \text{otherwise} \end{cases}. \quad (3)$$

The amplitude spectrum of the LP-DOT, simulated in MATLAB and incorporating the effects of truncation and digital approximation (quantization; 116 equidistant luminance levels), shows that the magnitude of the amplitude at spatial frequencies of 7 c/deg and above

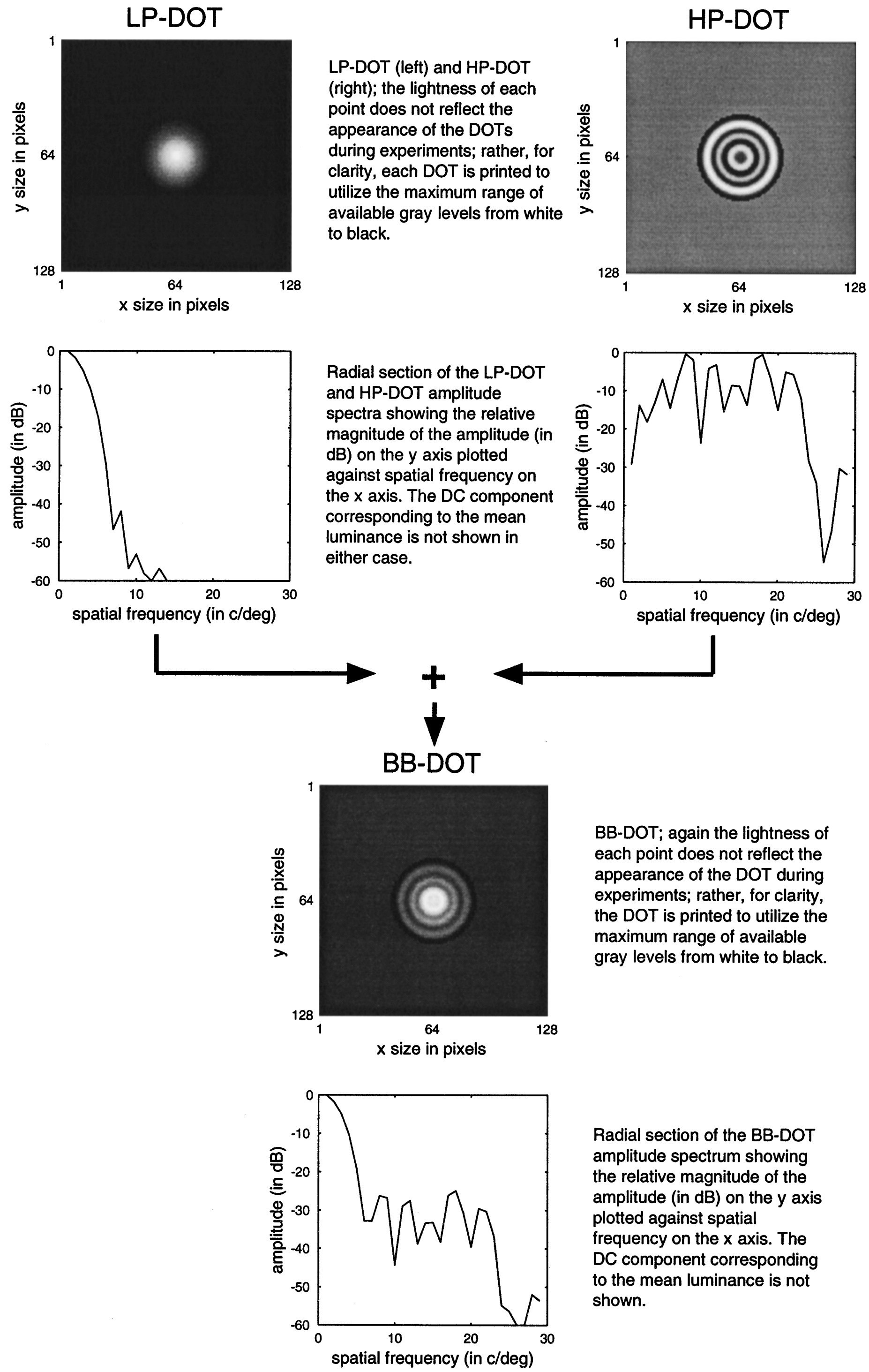


Fig. 5. Process of stimulus generation of the BB-DOTs shown in both the space and the spatial-frequency domain. Note that all three types of DOTs are printed with use of the maximally available range of gray levels and thus have much higher contrast than the ones actually displayed during the experiments. Further, the HP-DOT was appropriately scaled before being added to the LP-DOT; see the text for details.

was reduced by at least 45.8 dB relative to the amplitude at 1 c/deg along any direction in space. The Michelson contrast of the LP-DOT was 0.258 (Fig. 5).

2. *High-pass DOTs.* HP-DOTs were constructed by summing a number of circularly symmetric, cylindrically truncated 2-D gratings with spatial frequencies of 8, 10.67, 16, and 21.33 c/deg:

$$\text{HP-DOT}(x, y) = \begin{cases} \frac{1}{2}\cos(3\sqrt{x^2+y^2}) - \cos(4\sqrt{x^2+y^2}) & \text{if } \sqrt{x^2+y^2} \leq \pi \\ -\cos(6\sqrt{x^2+y^2}) + \cos(8\sqrt{x^2+y^2}) & \\ 0 & \text{otherwise} \end{cases}. \quad (4)$$

The contrasts and the phase relations of the components of the HP-DOT were chosen to reduce the contrast envelope of their sum, that is, to minimize, as far as is consistent with their high-frequency character, the luminance variation in the HP-DOTs. This precaution was necessary because of dynamic range constraints. Quantization and cylindrical truncation of the HP-DOT affected the spectral characteristics nontrivially, but the spectral energy of the HP-DOT below 5 c/deg was reduced by at least 38.7 dB relative to its total spectral energy (Fig. 5).

3. *Broadband DOTs.* BB-DOTs were obtained by adding together LP- and scaled HP-DOTs. The BB-DOT's Michelson contrast was 0.295 (achieved by adding a HP-DOT with a Michelson contrast of 0.114).

Figure 5 shows the generation of the BB-DOT and illustrates the three types of DOT and their spectra.

E. Visual Display

The experimental stimuli were displayed at a frame rate of 60 Hz on a linearized Eizo FlexScan T 560i-T monitor with a 0.26-mm trio pitch Triniton tube. The viewing distance, in a darkened room, was 178 cm during all experiments, and the background luminance was 45.5 cd/m^2. The display was driven by a Silicon Graphics Crimson VGX computer using a suitable linearizing lookup table. All stimuli appeared achromatic.

3. EXPERIMENT I: MOTION DETECTION

A. Method

The targets to be detected in a standard two-alternative forced-choice detection experiment were the horizontally oriented six-DOT target matrices to be detected against a background of static DOTs. Each trial consisted of two observation intervals, and the target appeared in exactly one of them. The probability that the target appeared in the first interval was 0.5 on each trial, and the observers' task was to indicate, by pressing buttons of a standard PC mouse, in which observation interval the target had appeared; the observers were not informed whether their responses had been correct. A second press initiated the next trial.

Signal duration was kept constant for each 20-trial session, and each observer was presented with at least seven different durations during an hour's observing, starting with the longest presentation time and proceeding to the shortest. Each observer ran each stimulus condition three times, so that each data point is based on 60 observations from a single observer. The authors and an experienced observer, all with normal or corrected vision, served as observers.

Three different signal conditions were employed: In the first two conditions, the target matrix moved as described in Subsection 2.B (motion detection); in one of those the moving target and the static background were LP-DOTs, and in the second all the DOTs were BB-DOTs. In the third condition the target matrix consisted of static LP-DOTs and the background of BB-DOTs. The background DOTs did not move in any condition.

B. Results

Figure 6 shows, separately for each observer, percent correct detection plotted against presentation time on semilogarithmic coordinates.

The curves show that, for all three observers, the detection task of static LP-DOTs in a static BB-DOT background (filled triangles, labeled "static") was the most difficult task; observers required signal durations of between 1500 and 3000 ms for 75% correct responses. The threshold for detecting motion in either BB- or LP-DOTs against the static backgrounds was in the region 17–200 ms and did not depend on the spatial-frequency characteristics of the stimuli (filled and open circles).

The data suggest that the presence or the absence of high-spatial-frequency information is not important in motion detection under these conditions.

4. EXPERIMENT II: MOTION-BASED IMAGE SEGMENTATION

A. Method

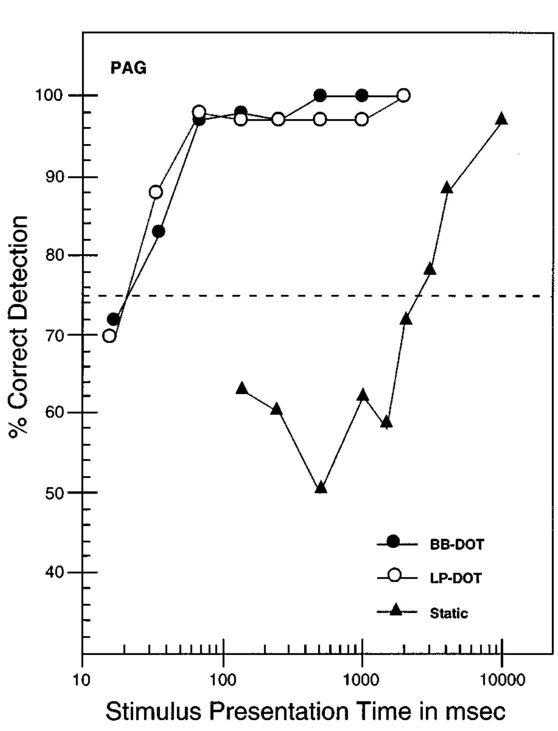
The observers' task in this two-alternative forced-choice discrimination experiment was to discriminate an interval containing a horizontally oriented matrix of six DOTs from one containing a vertically oriented matrix. Each trial consisted of two observation intervals. The horizontal matrix appeared in one observation interval, and the vertically oriented matrix appeared in the other. The probability that the target appeared in the first interval was 0.5 on each trial, and the observers' task was to indicate in which observation interval the target had appeared. Other conditions were identical to those of experiment I.

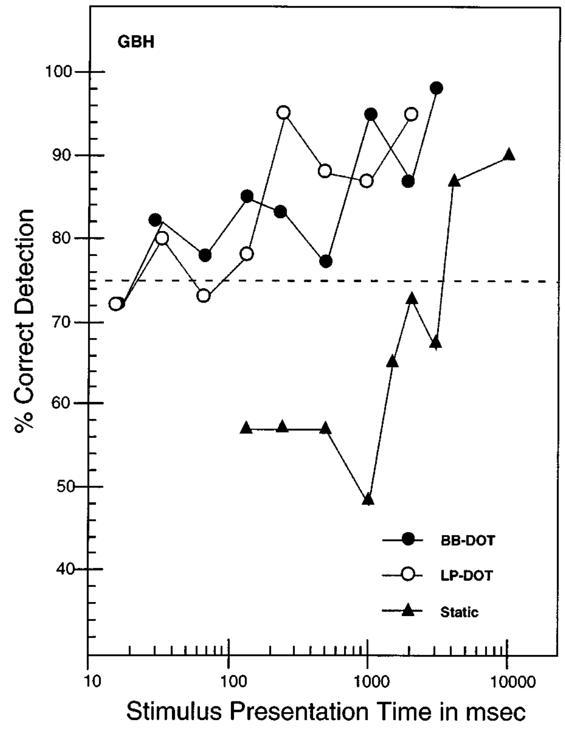
B. Results

Figure 7 shows, for each observer, percent correct discrimination plotted against presentation time. The time axis is logarithmic.

For all three observers discriminating static LP-DOTs from the static BB-DOT background (filled triangles, labeled "static") was most difficult. Observers required signal durations of between 1500 and 4000 ms for 75% correct discrimination. In both of the other conditions, when the targets differed from their static background by movement (filled and open circles), the observers required only approximately 150-ms stimulus presentation time to achieve 75% correct. This level did not depend on whether the DOTs were spatially low pass or spatially bandpass.

Thus the cues derived from the loss of high spatial frequencies alone are again far less effective than those de-





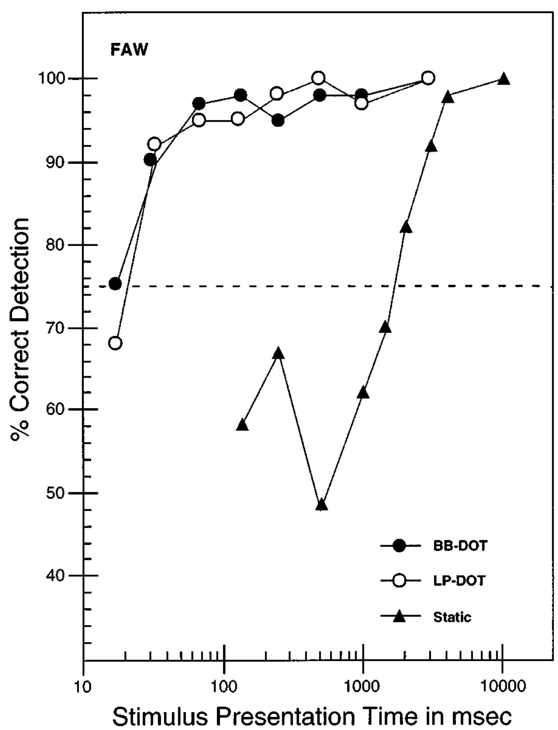


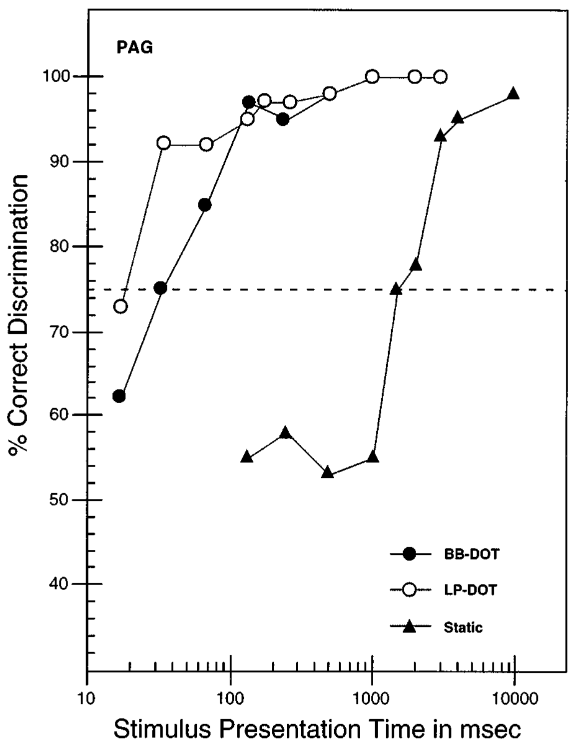
Fig. 6. Percent correct detection plotted against stimulus duration separately for each observer; the time axis is logarithmic. Data for three conditions are shown: (1) filled circles: motion detection, where both the target and background DOTs were BB-DOTs and the moving-target matrix was to be detected against static-background DOTs; (2) open circles: same as that for filled circles except that both target and background DOTs were LP-DOTs; and (3) filled triangles: form detection task, where a static-target matrix consisted of LP-DOTs and was to be detected against a background of static BB-DOTs.

rived from motion; they are so weak in comparison with the motion cue itself that they contribute little to motion-based image segmentation during everyday motion perception.

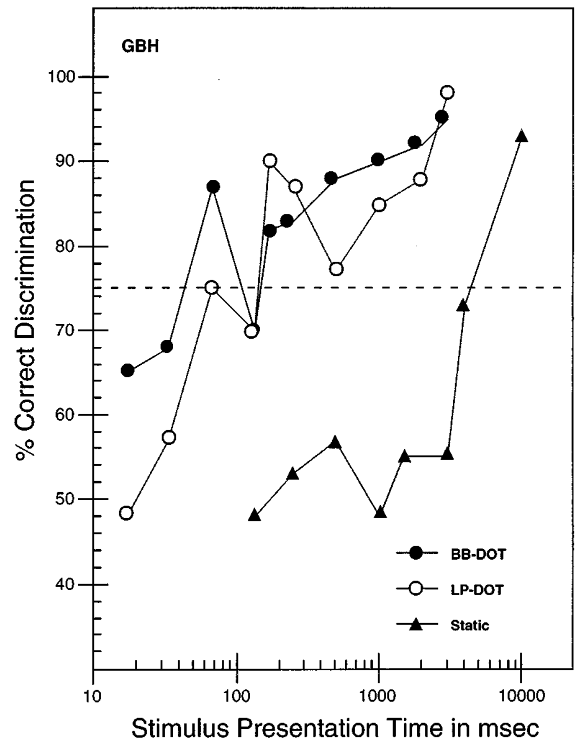
5. GENERAL DISCUSSION

There was no evidence from these experiments that changes in the perceived high-spatial-frequency content affects either motion detection or the extraction of form from motion. The perceptual loss in high-spatial-frequency content alone is not a reliable cue at durations where detection and segmentation based on motion are very good, although the blur associated with motion can be detected at longer presentation times.

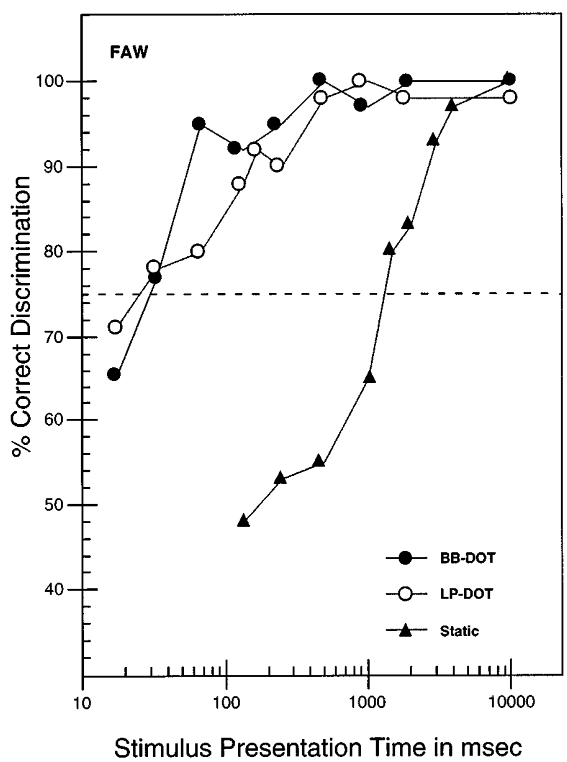
The spectral differences between BB- and LP-DOTs, which mimic the differences caused by motion, are easily



(a)



(b)



(c)

Fig. 7. Percent correct discrimination plotted against stimulus duration separately for each observer; the time axis is logarithmic. Data for three conditions are shown: (1) filled circles: extraction of form from motion, where the horizontally oriented moving-target matrix was to be discriminated from the vertically oriented moving matrix; moving matrices and the static background consisted of BB-DOTs; (2) open circles: same as that for filled circles except that moving matrices and the static background consisted of LP-DOTs; and (3) filled triangles: static form discrimination task, where a static horizontal matrix consisting of LP-DOTs was to be discriminated from a static vertical LP-DOT matrix against a background of static BB-DOTs.

detectable in isolation, i.e., when just one exemplar of each type of DOT is compared with the other. This is consistent with the ususal CSF and threshold elevation data presented in Fig. 1. The long presentation times required to solve the static task in experiment I and II imply, however, that the differences do not lead to what is frequently termed pop-out[24–26] or preattentive segregation.[27,28]

A. Stimulus Velocity

Since the amount of motion blur is a function of stimulus velocity,[3,10,11] there might be situations where motion blur is a more powerful cue, or indeed the only cue. For broadband stimuli like our BB-DOT, this would be true, however, only for velocities much higher than 4.6 deg/s, since the amount of motion blur is a monotonically increasing function of stimulus velocity.

For purely high-spatial-frequency stimuli the situation might be different. Here one may even want to argue that some form of extreme motion blur might be the only cue, in that moving high-spatial-frequency stimuli disappear when moving—as we found in our preliminary observations of moving HP-DOTs—or in a regime where a high-spatial-frequency grating moves extremely slowly and, quite possibly, eye movements could render the motion signal unreliable.[29] In the natural world, however, objects are generally not composed solely of high spatial frequencies,[2] and our experiments were designed to assess the influence of motion blur as a cue to motion in everyday situations.

B. Stimulus Contrast

Before the usefulness of high-spatial-frequency information as a motion cue is rejected, however, we must consider a possible objection that might arise from the low stimulus contrasts employed. It might be argued that the visible energy contained in the HP-DOT, that is, its spectral energy weighted by the CSF, was too small compared with the energy in the LP-DOT and that some form of masking by the LP-DOT prevented the effective loss of the HP-DOT from being detected.

This objection can be tested by raising the contrast of the HP-DOT component of the BB-DOT. In two additional experiments—one motion detection and one motion-based image segmentation experiment—the contrast of the high-spatial-frequency component of the BB-DOT, that is, of the added HP-DOT, was increased fivefold. The Michelson contrasts of the LP- and the BB-DOTs in these experiments were 0.507 and 0.970, respectively. To achieve this within the dynamic range of the display, the background luminance was reduced to 17.2 cd/m^2. This change in mean luminance should not, however, interfere with the generality of the results because the CSF is qualitatively similar over a much wider range of luminances.[6,30]

The methods were identical to those of experiments I and II apart from the fivefold increase in the contrast of the HP component of the BB stimuli and the change in mean luminance. Only two experimental conditions were run: moving LP-DOTs to be detected/discriminated from a static LP-DOT background and moving BB-DOTs to be detected/discriminated from a static BB-DOT background; the purely static detection and discrimination condition was omitted (static LP-DOT target matrix embedded in static BB-DOT background). For both observers, the authors, there was no qualitative difference between the results obtained in the low- and high-contrast conditions. This excludes the possibility that the results of experiments I and II were the result of some form of masking.

C. Conclusion

None of the experiments showed any evidence that high-spatial-frequency energy, or its absence, influences motion detection or image segmentation based on motion. Since motion perception was probed in all directions, for different stimulus elements at different contrasts and background luminances, we are led to conclude that the cue that could be derived from motion blur does not contribute to motion detection or image segmentation, at least up to the velocity employed in this study (4.6 deg/s).

ACKNOWLEDGMENTS

This research was carried out at the Department of Physiological Sciences, The Medical School, The University of Newcastle-upon-Tyne, and was supported by grant G9030578 from the Medical Research Council/ Engineering and Physical Sciences Research Council/ Engineering Sciences Research Council to A. C. Hurlbert and from the Science and Engineering Research Council to A. M. Derrington. We thank A. C. Hurlbert and A. M. Derrington for allowing us to use their equipment. Felix A. Wichmann held a Wellcome Trust Vacation Scholarship and is now supported by a Wellcome Trust Mathematical Biology Studentship and a Jubilee Scholarship from St. Hugh's College, Oxford. We are particularly grateful to David Bramwell for his programming help, to Karl Gegenfurtner, Per Møller, and Stanley Klein for helpful discussion and to Jeremy Hill for his comments on an earlier version of the manuscript.

Part of this work was presented as a paper at the 18th European Conference of Visual Perception in Tübingen, Germany,[31] and at the 1996 Annual Meeting of the Optical Society of America in Rochester, N.Y.[32]

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