Journal of Experimental Psychology:
Human Perception and Performance
1995, Vol. 21, No. 2, 231-238

0096-1523/95/$3.00

Multiple Images Appear When Motion Energy Detection Fails

P. J. Bex
College of Cardiff, University of Wales

G. K. Edgar
British Aerospace

A. T. Smith
University of London

Under certain conditions, multiple images trail behind a target moving across a cathode ray oscilloscope. Given the relatively sluggish temporal response of the visual system, it is surprising that when an image is rapidly displaced, multiple images are not seen under most circumstances. The authors have explored the conditions under which multiple images appear. The velocity at which multiple images first appear (aliasing velocity) was recorded across a range of image update rates for a drifting bar and for band-pass and low-pass filtered bars. Multiple images were found to appear when a fixed spatial displacement was exceeded between image updates. The value of this displacement was approximately invariant with drift speed. The effects on aliasing velocity of band-pass and low-pass filtering are similar to those reported for motion detection after comparable manipulations of a random dot kinematogram (R. Cleary & O. J. Braddick, 1990a, 1990b). The findings suggest that multiple imaging occurs when motion energy detection fails.

One problem with computer-generated moving images is that cathode ray oscilloscopes (CROs), on which they are usually displayed, are updated at a finite rate. Consequently, it is possible to simulate motion only by displacing a stationary image to a new position spatially discrete from its former location. Because the update rate of a CRO is limited, as the image moves faster, the distance it must be moved on each update becomes greater. Under certain conditions the apparent motion of sampled moving objects is indistinguishable from real motion (Watson, Ahumada, & Farrell, 1986; Burr, Ross, & Morrone, 1986). However, at low update rates and high velocities, the perception of smooth motion may be lost. Any misperception of motion that arises from a low sampling rate is referred to as temporal aliasing. One form of temporal aliasing is the appearance of multiple images trailing behind a moving target presented on a CRO.

The phenomenon of multiple imaging has primarily been used to measure visual persistence. Allport (1970) measured visual persistence using a radius painted on a rotating disk. When viewed directly, the radius was seen as a single rotating line. However, when viewed illuminated by a stroboscope at low flash rates (about 10 Hz), a single line was seen adopting a rapid succession of radial positions around the disk. At high strobe rates it appeared as a sharply defined fan of radii rotating as a group, and the perceived number of radii increased with flash rate. Farrell (1984) replicated these findings using a rotating bar displayed on a CRO with presentation rate adjusted by varying the image update rate. Observers were required to report the number of lines simultaneously visible. Farrell found that the perceived number of rotating lines increased linearly with the rate of stimulus presentation with a slope that was proportional to the spatial separation between the successive radii.

The linear velocity varies along the length of a rotating radius. Farrell, Pavel, and Sperling (1990) avoided this problem by measuring persistence of bars in linear apparent motion. Stimulus lines were presented in successive positions moving in opposite directions above and below a fixation point. Observers were required to indicate whether they perceived all lines simultaneously, thus seeing a grating (i.e., the final presentation occurred while the first and subsequent presentations persisted visually). Visual persistence was found to increase with spatial separation up to 0.24° of visual angle.

Farrell et al. (1990) suggested that multiple imaging may involve some form of gradual neural response decay. Thus, repeated presentation of a time-sampled moving stimulus would result in multiple images if the second presentation occurred before the first had fully decayed. Farrell et al. postulated that the time course of visual persistence may be affected by a simple gain mechanism for modulating the duration of visual persistence as a function of the distance separating stimuli. Thus, the presence of adjacent stimuli reduces the time course of the neural response, and the effect is greatest for the closest stimuli. Di Lollo and Hogben (1985, 1987; Hogben & Di Lollo, 1985) suggested that

P. J. Bex, Vision Research Unit, Department of Psychology, College of Cardiff, University of Wales, Cardiff, Wales; G. K. Edgar, Sowerby Research Centre, British Aerospace, Bristol, England; A. T. Smith, Department of Psychology, University of London, Surrey, England.

This research was supported by a Science and Engineering Research Council studentship and by British Aerospace.

Correspondence concerning this article should be addressed to P. J. Bex, who is now at McGill Vision Research Centre, Department of Ophthalmology, McGill University, 687 Pine Avenue, West, Room H4-14, Montreal, Quebec, Canada H3A 1A1.

the data are readily explained by a system of local inhibition of the kind proposed by Breitmeyer and Ganz (1976). Thus, a response to a stimulus inhibits the responses of nearby receptors, and the strength of inhibition decreases with separation.

The underlying assumption of the investigations described above is that two (or more) images will be seen when the neural representations of a single image presented in successive locations exist simultaneously. Usually, stimulus lines displaced between updates on a CRO appear to be in apparent motion, and the larger the spatial displacement, the higher the velocity. It is surprising, given the relatively sluggish temporal response of the human visual system, that when an image is rapidly displaced, multiple images are not seen under most circumstances.

Normally, a single image is seen in apparent motion, which suggests active suppression of the multiple images that would otherwise be perceived. We have investigated the effects of motion perception on multiple imaging and evaluated the hypothesis that multiple images appear when there is a failure in motion energy detection. Thus, when representations of two images coexist, if motion has been detected, the presence of only one moving image is inferred. If motion has not been detected, the presence of multiple targets is inferred. If this is the case, the velocity (step size) at which multiple images first appear will always be that at which motion perception fails. This will occur when a fixed spatial displacement is exceeded between image updates. To investigate this, we measured the drift speed of a bar at which multiple images first appear (aliasing velocity) for images at a range of different image update rates in Experiment 1.

General Method

Participants

Ten paid participants served as observers in Experiment 1. One naive participant and one of the authors (P. J. Bex) served as observers in Experiments 2 and 3. All participants had visual acuity of 6/6 or better and no history of ocular ill health.

Apparatus

Stimuli were generated by a grating generator (Millipede VR1000 Cambridge, United Kingdom) under the control of a PC microcomputer. Stimuli in Experiment 1 were presented on a Joyce display with a 200-Hz frame rate and white ^{4}P phosphor masked to provide a 5° circular aperture. The maximum and minimum luminances recorded with a photometer were 94.9 and 17.2 cd/m^2, respectively. In Experiments 2 and 3, we used a Hewlett Packard 1332A X-Y display with a 122-Hz frame rate and white ^{4}P phosphor masked to provide a 3.75° circular aperture. The maximum and minimum luminances were 32.9 and 0.2 cd/m^2, respectively. A forehead rest maintained a comfortable, correct viewing distance. The room was lit at a constant, dim level.

Stimuli

In all conditions, the stimulus was a single vertical line which was moved horizontally across the aperture in either direction. In Experiment 1 the line was 0.023° in width and white on a black background. The Michelson contrast of the stimulus was 69%. Different update rates were achieved by moving the stimulus line either every time the display was refreshed (200 Hz) or after a certain number of refreshes (i.e., every other refresh = 100 Hz, etc.)

Procedure

The observer was seated at the required viewing distance and instructed to fixate on a small spot in the center of the screen. Before the start of the experiment the screen was blank at the mean luminance for 1 min. At the end of the minute a tone sounded to signal the start of the experimental trials. The observer was instructed to press either of the two response buttons when ready, which initiated the set of trials. A vertical line appeared 2 s after each button press and moved horizontally across the screen through the fixation point. Direction of movement was varied randomly from trial to trial. This helped prevent participants from anticipating the start point and tracking the stimulus. In a pilot study, no significant differences were found for three stimulus durations (200, 600, and 1000 ms), hence a stimulus duration of 600 ms ± 10% at random was used. The randomization ensured a different start point so as to prevent observers from anticipating the path of the line. Although 600 ms is sufficiently long to initiate pursuit eye movements, steady fixation on the central spot by participants ensured that the stimulus duration did not affect the results.

A single-interval yes–no design was used. After each trial, the participants were required to indicate, by pressing one button, whether they had seen "one line" or "more than one line." In pilot studies, it was ascertained that observers were able to distinguish two bars when separated by a single pixel at all velocities to be used in the main experiment. Even with zero separation, observers could tell that two bars were present because of the wide appearance of the bar. This eliminated the possibility that multiple imaging might be underestimated because the multiple images could not be resolved. Observers were instructed to ignore other effects that may have been caused by other types of temporal aliasing (e.g., jerky motion). There was a 2-s blank interval between each trial. Each run consisted of 30 trials. On any run the update rate was held constant, but the velocity of the line was varied from trial to trial. As there was no distinct point at which the percept changed from one line to more than one line, a criterion for smooth motion was set at 50% (i.e., the velocity at which the participant reported seeing a single line on 50% of trials at that update rate). The speed of the stimulus on each trial was set according to a modified parameter estimation by sequential testing routine (Taylor & Creelman, 1967) designed to converge on the 50% point. The 50% point was inferred by fitting a psychometric function to the data (Weibull, 1961). Only a relatively limited range of velocities could be presented because the stimulus could only be moved a constant whole number of lines on each refresh. To use intermediate velocities would involve different displacements for each screen refresh (e.g., one and two pixels on alternate frames), which would be inappropriate for a study of temporal aliasing.

There were 30 trials per run, and four runs per observer. The order in which the different conditions were tested was randomized for each participant.

Experiment 1: Effects of Image Update Rate on Multiple Imaging

Procedure

The velocity at which multiple images first appeared was recorded as described in the General Method section for a simple drifting bar over a range of image update rates.

Results and Discussion

The velocities at which observers saw multiple imaging with a probability of 50% are plotted as a function of update rate in Figure 1A. Each point is the mean for all ten observers. The points are well fitted by the straight line shown (r^2 = .998), suggesting a linear relationship with a unity slope between image update rate and the speed at which multiple imaging occurs. This relationship indicates that multiple images first appear when a constant spatial displacement is exceeded between image updates. For our stimulus the critical displacement is 4 arcmin. Typical psychometric functions at two update rates are shown in Figure 1B. The steepness of the function demonstrates the sudden transition from the appearance of single to multiple images. The fact that the phenomenon is governed by spatial displacement and is independent of update rate (or stimulus onset asynchrony) suggests that it does not arise directly from limitations of temporal integration but that some other factor controls the appearance of multiple imaging.

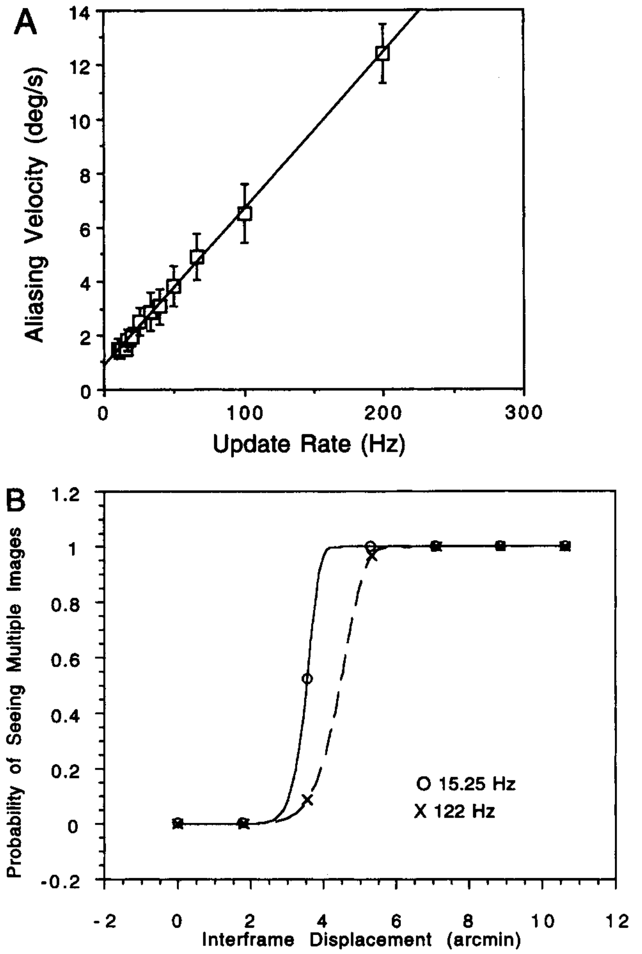

Figure 1. (A) Velocity at which the probability of seeing multiple images is 50% for a simple drifting bar. Data show the results for 10 observers. The abscissa represents the range of monitor update rates used. Error bars represent ±1 *SE.* (B) Typical psychometric functions of one observer (P.B.) at two update rates, demonstrating the transition from the appearance of single drifting lines to multiple drifting lines.

The results are consistent with the suggestion that the failure of motion energy detection is involved in the appearance of multiple images. Motion detection in random dot kinematograms has also been shown to be limited by a fixed spatial displacement for a given image (Braddick, 1974). The precise value of the displacement at which multiple images appear is considerably different from typical estimates of d_{max}; however, as discussed in the next two sections, the value of d_{max} has been shown to vary considerably with spatial structure of the stimulus. RDKs are used in motion detection experiments because they contain no explicit features. Consequently, motion that is detected between two frames is presumed to be detected by a system operating on spatiotemporal energy variations in the stimulus (Adelson & Bergen, 1985; van Santen & Sperling, 1985; Watson & Ahumada, 1985). The energy spectra of RDKs are very broad, and it is difficult to evaluate the contribution of specific spatial frequency components to the overall percept of motion. Consequently, several researchers have used filtering techniques to determine the role of spatial structure in motion energy detection. Specifically, the effects of band-pass and low-pass filtering on d_{max} have been explored in some detail. The results of these experiments have contributed to the understanding of motion detection in stimuli with broad energy spectra. In Experiments 2 and 3 the effects on aliasing velocity of manipulations of the spatial structure of a bar are explored.

Experiment 2: Effects of Band-Pass Filtering on Multiple Imaging

Several researchers have reported an increase in d_{max} for band-pass filtered RDKs (Bischof & Di Lollo, 1990; Chang & Julesz, 1983, 1985; Cleary, 1990; Cleary & Braddick, 1990a). Chang and Julesz (1983) found that d_{max} in RDKs was affected by spatial frequency filtering. For an unfiltered RDK, these researchers reported d_{max} in the typical range (about 12.5 arcmin). However, d_{max} increased for band-pass filtering (3–5.8 cycles/deg passband) to about 18 arcmin. For band-pass filtered RDKs, d_{max} has been shown to be inversely related to the center frequency of the passband (Bischof & Di Lollo, 1990; Chang & Julesz, 1983; Cleary, 1990; Cleary & Braddick, 1990a). It has been argued that motion detection in band-pass RDKs is mediated by motion energy correlators whose optimal spatial frequency is tuned to the passband of the filtered RDK (Bischof & Di Lollo, 1990). The spatial limits of these energy detectors is inversely related to spatial frequency tuning (i.e., low spatial frequency detectors have a larger receptive field). Consequently, motion in band-pass filtered RDKs from a lower passband is detected by motion energy detectors tuned to a lower spatial frequency, and these detectors respond optimally to larger spatial displacements (although the displacement is approximately constant in terms of fractions of a cycle).

The energy spectrum of an unfiltered RDK is broad and flat, and there may be complex relationships between energy detectors tuned to different spatial scales (Cleary & Braddick, 1990b). Several researchers have attempted to overcome this problem by analyzing motion detection of simple sine wave grating stimuli. The sine wave kinematogram contains two frames, each of a sine wave but with the sine wave on the second frame displaced by a variable amount. Motion detection in sine wave kinematograms has been shown to be optimal for displacements of 1/4 cycle by measuring direction discrimination (Bischof & Di Lollo, 1990; Nakayama & Silverman, 1985). This 1/4-cycle fraction is constant across spatial frequencies within the visible spectrum. Displacements of a sine wave grating greater than 1/2 cycle appear to move in the opposite direction because of aliasing.

The research described above demonstrates that the upper displacement limit for the detection of energy-based motion varies with the spatial structure of the target. If multiple imaging occurs when energy-based motion detection between updates fails, then aliasing velocity should vary with the spatial structure of an image in the same way that d_{max} varies with the spatial structure of RDKs. Thus, aliasing velocity should be higher for band-pass filtered bars from a lower passband because the maximum spatial displacement for motion energy detection is greater for these stimuli. Similarly, aliasing velocity should vary with center frequency for band-pass filtered bars, and this value should correspond to a 1/2-cycle step size between image updates. These specific predictions were explored in Experiment 2. The aliasing velocities of band-pass filtered bars were recorded for a range of different passbands.

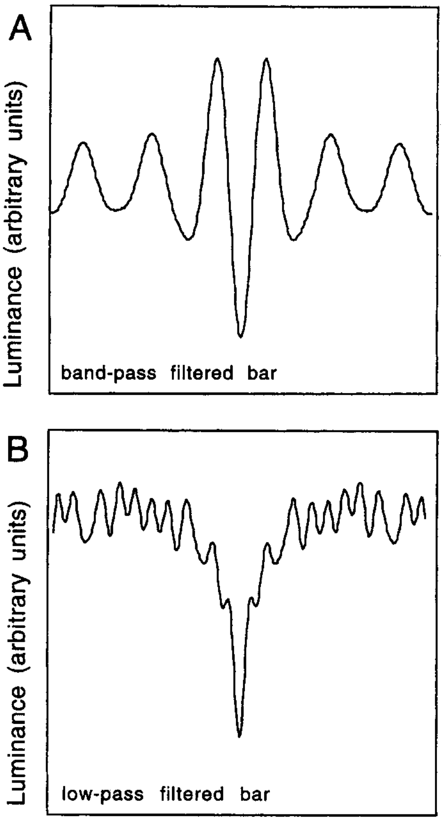

Figure 2. Illustration of the luminance profile of stimuli used in Experiments 2 and 3. (A) Band-pass filtered bar; the result of the addition of 21 sine waves of equal amplitude in appropriate phases such that the troughs converged at one point. All the sine waves were sampled from one of the seven octaves in the spatial frequency range 0.2–25.6 cycles/deg. (B) Low-pass filtered bar; the result of low-pass filtering a standard bar constructed by the addition of 21 sine waves (three from each of the seven octaves in the range 0.2–25.6 cycles/deg). Low-pass filtering was simulated by the removal from the standard of sine waves with spatial frequencies above the cutoff.

Stimuli and Procedure

In Fourier terms, the simple bar used in Experiment 1 is paradoxically a complex one-dimensional stimulus, because it contains energy across a broad spatial frequency spectrum. In Experiment 2, seven vertical bars were constructed by the addition of 21 sine waves of equal amplitude, each from one of the seven octaves in the range 0.2–25.6 cycles/deg. A logarithmic separation between components was employed because spatial frequency–selective channels have been shown to have a bandwidth that is approximately constant in logarithmic terms (Campbell & Robson, 1968). The sine waves were adjusted in phase such that all the troughs converged at one point, producing a bar with blurred edges. The final bars were black with blurred edges on a gray background that contained low contrast ripples. Bar width and ripple frequency increased with center frequency. An illustration of the luminance profile of such a band-pass filter bar is shown in Figure 2A. Each bar was moved horizontally across the aperture in either direction. The luminance of the display was variable with 12-bit resolution, which permitted fine control of sine wave amplitude.

The 50% point for seeing multiple images was recorded as described in Experiment 1 for 1-octave band-pass filtered bars. The order in which the stimuli were presented was randomized. Stimuli were presented at 61 Hz. This update was chosen because motion did not appear jerky and multiple images appeared at a velocity lower than 122 Hz, making the task easier for the participants to perform.

Results and Discussion

The velocities at which observers reported seeing multiple images with a probability of 50% are plotted as a function of the center frequency of the passband in Figure 3. For stimuli constructed from sinusoids in the lower three octaves, aliasing velocity was very high, and it was not possible to record it reliably. However, for those recordings

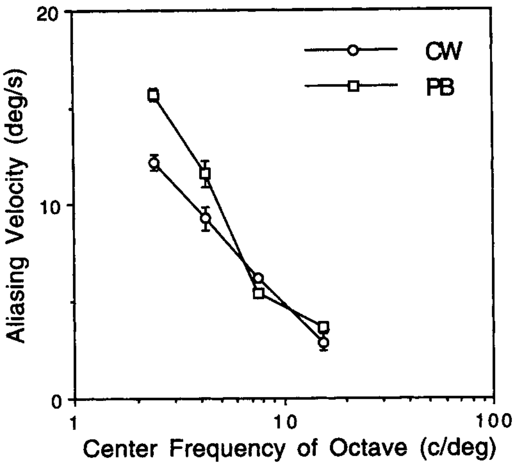

Figure 3. Velocity at which the probability of seeing multiple images is 50% for a drifting band-pass filtered bar. The abscissa represents the spatial frequency of the center of the one-octave passband. Data show the results for two participants (P.B. and C.W.) observing a drifting bar on a monitor with an update rate of 61 Hz. Error bars represent ±1 *SE*. Frequency is measured in cycles per degree (c/deg).

obtained, there is an approximately linear relationship between the velocity at which multiple images first appear and the center frequency of the stimulus.

The number of cycles of the lower spatial frequency cutoff traversed between successive updates is shown in Figure 4 for each participant. At the aliasing velocity, this displacement is approximately 0.5 cycles but increases slightly with spatial frequency. These findings are similar to those reported for sine wave kinematograms and band-pass filtered RDKs (Bischof & Di Lollo, 1990). This similarity is in good agreement with the suggestion that multiple images appear when there is a failure of motion detection.

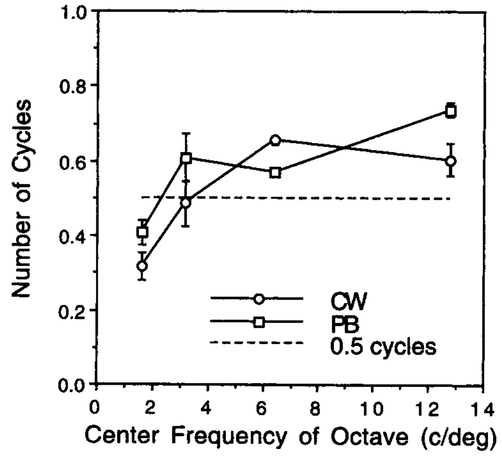

Figure 4. Number of cycles of the lowest spatial frequency sine wave stepped between frames at aliasing velocity. The abscissa represents the center spatial frequency of the octave from which the sinusoids were sampled. Error bars represent ±1 *SE*. Data are plotted for two observers (P.B. and C.W.) from the data in Figure 3. Frequency is measured in cycles per degree (c/deg).

Experiment 3: Effects of Low-Pass Filtering on Multiple Imaging

Several researchers have reported an increase in motion energy detection for low-pass filtered RDKs (Chang & Julesz, 1983, 1985; Cleary & Braddick, 1990a, 1990b). Chang and Julesz (1983) found that d_{max} in RDKs increased after low-pass filtering (0.2–2.8 cycles/deg). Similar observations for the effects of low-pass filtering have been made by Chang and Julesz (1985) and Cleary and Braddick (1990b). Both groups of researchers reported that for low-pass filtered RDKs, lowering the cutoff of the filter produced no effect initially. However, when the cutoff was 4 cycles/deg or lower, there was an approximately linear relationship between the cutoff of the low-pass filter and d_{max}. Low-pass filtering lowered the contrast of the filtered image. However, when contrast was normalized to 50%, there was no effect of contrast of the filtered RDK.

From the effects of low-pass filtering on motion detection in RDKs, it was predicted that multiple imaging for low-pass filtered bars would behave similarly. Multiple imaging was expected to be initially unaffected by low-pass filtering. However, when the cutoff of the low-pass filter was below a critical value (4 cycles/deg for RDKs), multiple imaging was expected to occur at higher velocities.

Stimuli and Procedure

The basic stimulus was a vertical bar constructed by the addition of 21 sine waves of equal amplitude: three sine waves in each of the seven octaves in the range 0.2–25.6 cycles/deg. The sine waves were adjusted in phase such that all the troughs converged at one point, producing a black bar with blurred edges on a gray background that contained low-contrast ripples. Spatial filtering of the bar could be simulated by removing sine waves of specific spatial frequencies. To simulate low-pass filtering, we removed the high spatial frequency sine waves of frequencies above the cutoff from the stimulus (see Figure 2B). Subtraction of a sine wave reduced the contrast of the remaining stimulus. Two conditions were measured after low-pass filtering: In the first, the amplitude was raised to maintain the overall contrast at maximum, whereas in the second the contrast was left to fall as sine waves were removed.

The 50% point for seeing multiple images was recorded as described above for low-pass filtered bars at a range of different cutoffs in random order. Stimuli were presented at 61 Hz. For each cutoff, two separate conditions were recorded, also in random order: contrast normalized and contrast not normalized.

Results and Discussion

The velocities at which the observers reported seeing multiple images with a probability of 50% are plotted as a function of upper cutoff spatial frequency in Figure 5. Initially, there is little effect of low-pass filtering. However, when the cutoff is below 9 cycles/deg, there is a marked increase in the velocity at which multiple images appear. Nonnormalized stimuli show a slightly lower aliasing ve-

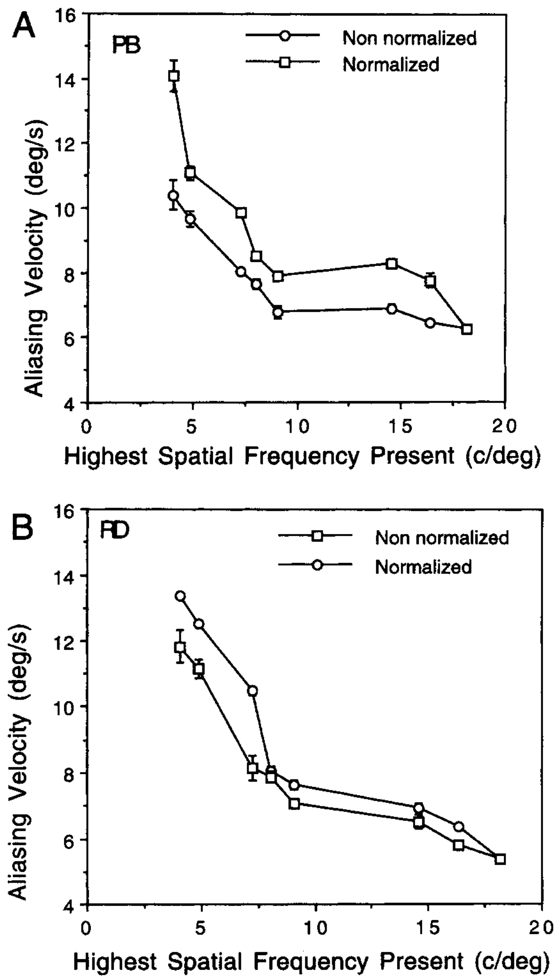

Figure 5. Velocity at which the probability of seeing multiple images is 50% for a low-pass filtered drifting bar for (A) observer P.B. and (B) observer R.D. watching a drifting bar on a monitor with an update rate of 61 Hz. The abscissa represents the highest spatial frequency present in the stimulus after filtering. Open circles represent the condition in which contrast was normalized, and open squares represent the condition in which contrast was allowed to fall with successive removal of sine wave components. Error bars represent ±1 *SE*. Frequency is measured in cycles per degree (c/deg).

locity than normalized stimuli, but the trend is the same. Removal of high spatial frequencies results in the bar becoming wider and more blurred, and aliasing velocity becomes higher. Consequently, below the lowest spatial frequency shown (4 cycles/deg), it was not possible to make reliable observations of when multiple imaging occurs because the bar drifted at very high velocity.

The trends are very similar to the results reported for d_{max} for low-pass filtered RDKs (Chang & Julesz, 1983; Cleary & Braddick, 1990b). In particular, the trend is similar to that observed by Cleary and Braddick (1990b), who found no initial effect of low-pass filtering followed by increases in d_{max} after a critical cutoff (3.6 cycles/deg). There was no significant effect of contrast. Again, the results are consistent with the hypothesis that multiple images appear when there is a failure in motion energy detection. The suggestion by Cleary and Braddick (1990b) that high spatial frequencies mask low spatial frequencies accounts well for the current data. The initial flat function also confirms their suggestion that the visual system is inefficient at encoding high spatial frequencies. However, it should not be overlooked that there is a considerable difference in the cutoff at which the elbow in the function occurs (9 cycles/deg for multiple imaging and 3.6 cycles/deg for d_{max}), although the spatial structure of both stimuli differ broadly. There is also similarity with the trends observed by Morgan and Fahle (1992; Morgan, 1992), whose data demonstrate no initial effect of element size on d_{max} for RDKs and subsequent increases in d_{max} with element size above 9 arcmin. These authors argue that the data are consistent with the existence of a visual filter that is insensitive to high spatial frequencies (Morgan & Fahle, 1992) and that the passband of the filter is limited by a receptive field size (possibly of magnocellular units) of approximately 10 arcmin. This also accounts well for the current data.

General Discussion

The results indicate that there is a linear relationship between the update rate of an image and the velocity at which multiple imaging first occurs. The unity slope indicates that the spatial displacement between image updates at which multiple images first appear is approximately constant. The value of the critical spatial displacement is approximately invariant with velocity. For band-pass filtered images, aliasing velocity is linearly related to the center frequency of the passband. At aliasing velocity, the spatial displacement corresponds to a step size of approximately 0.5 cycles of the lower cutoff of the passband. The maximum spatial displacement may be extended by low-pass filtering below a cutoff of 9 cycles/deg. The similarity between the current data and those reported for motion detection after similar manipulations of RDKs suggests that motion energy detection is involved in the appearance of multiple images. The results demonstrate that the aliasing velocity is the velocity at which energy-based motion detection fails (Adelson & Bergen, 1985; van Santen & Sperling, 1985; Watson & Ahumada, 1985).

Phosphor persistence has recently been shown to have confounding effects for oscilloscopic displays (Groner et al., 1993). However, Westheimer (1993) recorded the rate of ^{31}P decay using a photomultiplier tube and found satisfactory decay rates to 2% of maximum after approximately 2 ms. Westheimer attributed this discrepancy to the indirect nature of Groner et al.'s recordings. In the present study, image update rate was manipulated by displacing the image after the required number of frames with no interstimulus interval (ISI). The interval between frames in our experiments was never less than 5 ms and was sometimes much more. Even allowing for somewhat slower decay than that reported by Westheimer, it is unlikely that the multiple imaging resulted from phosphor persistence in our experiments. We have not attempted to measure the time course of visual persistence, which would be affected by phosphor persistence. The important observation is that when the spatial displacement is small, there is no visually persistent image. The data in Experiment 1 were obtained from white bars on black background, where persistent phosphor would produce maximum confounding effect. However, we have made identical recordings across a range of contrasts including dark bars on light backgrounds. In the latter conditions, excessive phosphor persistence would overlay the multiple black bars, but multiple images of black bars could be seen at the aliasing velocity.

Several researchers have explored the effect of spatial frequency on the time course of visual persistence. Meyer and Maguire (1977) reported that the perceived duration of sine wave gratings increased with spatial frequency using a continuity measure for a flickering grating. However, Long and Sakitt (1981) observed that this effect was confounded by the number of cycles of the sine wave grating that were visible, and when this was controlled for, the effect was reversed. Di Lollo and Woods (1981) measured visual persistence for blurred stimuli by a variation of Eriksen and Collins's (1967) method. This method involves detection of a missing element from an array presented sequentially in two frames after a variable ISI. The task is simple if all presented elements are simultaneously available (if the first frame is visually persistent throughout the ISI) but is otherwise a matter of chance. Di Lollo and Woods reported that visual persistence was shorter when an image was defocused, confirming the findings of Meyer and Maguire. Overlooking the findings of Long and Sakitt, one may argue that the results for filtered stimuli reflect the decrease in visual persistence observed for lower spatial frequencies. However, this fails to explain the "elbow" in the functions in Figure 5, because there is no such elbow in the data for visual persistence. Moreover, the shorter duration of visual persistence for lower spatial frequencies should cause the appearance of multiple images at a smaller spatial displacement. This is because the decay rate is faster for these stimuli, and a persistent image would fall below perceptual threshold more rapidly. The results of Experiments 2 and 3 show that, in fact, lower spatial frequency bars are visible after larger spatial displacements. It may be concluded that the results do not reflect the shorter duration of visual persistence for lower spatial frequencies.

The appearance of multiple images at the point at which energy-based motion perception fails is consistent with the hypothesis that when two images yield simultaneous neural activity, if motion energy is detected, the presence of one drifting image is inferred. The process may operate by an inhibitory system (Breitmeyer & Ganz, 1976; Farrell et al., 1990) that has a limited spatial area of effect. This spatial area may covary with receptive field size of motion detectors (Bischof & Di Lollo, 1990). The absence of multiple images when energy-based motion is detected means that the problem of multiple imaging may be reduced if motion detection is facilitated between image updates. This may be achieved by increasing the image update rate such that the spatial displacement between updates is below d_{max}. Low spatial frequency band-pass filtering and low-pass filtering that extend d_{max} in RDKs also reduce the problem of multiple imaging.

Summary and Conclusions

For a simple bar moving horizontally across a cathode ray oscilloscope, there is a linear relationship between the update rate of the monitor and the velocity at which multiple images first appear (aliasing velocity). The linear relationship indicates multiple images first appear when a constant spatial displacement is exceeded at the simulated velocity. The value of this displacement is independent of velocity. Motion energy detection in spatially complex images (RDKs) has also been shown to be limited by a fixed displacement for a given image.

One octave band-pass bars have an aliasing velocity inversely proportional to the center frequency of the passband. This velocity corresponds to a spatial displacement of approximately 0.5 cycles of the lowest spatial frequency in the image. This finding is similar to that reported for motion energy detection in sine wave kinematograms and band-pass filtered RDKs (Bischof & Di Lollo, 1990).

Low-pass filtering of a bar permits increases in the velocity (i.e., increased spatial displacement between frames of apparent motion) at which multiple imaging first occurs. The removal of only very high spatial frequencies has little effect on aliasing velocity. However, after low-pass filtering below a critical frequency (9 cycles/deg), there is an inverse relationship between the upper cutoff spatial frequency and aliasing velocity. These results are similar to those reported by Cleary and Braddick (1990b) for d_{max} in low-pass filtered RDKs and are consistent with their suggestion of "masking" of low spatial frequencies by higher ones. There is also agreement with the results of Morgan (1992) and Morgan and Fahle (1992) for the effects of RDK element size on d_{max}. Our data are consistent with these authors' suggestion of the existence of an early spatial frequency filter in the visual system.

Our results indicate that the time course of persistent images is affected by the perception of motion. When neural representations of two images coexist, if motion is detected, the presence of only one moving image is inferred. If motion is not detected, the presence of multiple targets is inferred. Therefore, the problem of multiple imaging may be reduced if motion detection is facilitated between image updates. This may be achieved by increasing the image update rate so that spatial displacement remains below the critical displacement limit. Low spatial frequency band-pass filtering and low-pass filtering, which extend d_{max} in RDKs, also reduce the problem of multiple imaging.

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Received August 20, 1993
Revision received February 23, 1994
Accepted April 21, 1994 ■