

CONTRAST SENSITIVITY AT HIGH VELOCITIES

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Abstract—Measurements were made of the contrast required to see the direction of motion of drifting gratings (Part 1) and of moving bars (Part 2). The spatial frequency at which least contrast is required to see sinusoidal gratings decreases as their velocity increases, but peak sensitivity is identical at all velocities up to 800 deg/sec. Similarly, the wider a single bar, the higher the velocity at which it is best visible. A bar 80 deg wide is best seen when moving at 300–500 deg/sec, and can be seen, and its direction of motion identified, even when moving at 10^4 deg/sec. These results show that motion does not diminish the visual passband, but instead slides the spatial frequency window along the spatial frequency scale, maintaining peak sensitivity at a temporal frequency of about 10 Hz (at photopic luminances).

INTRODUCTION

When the eyes are stationary, and light ample, the human visual system peaks in sensitivity at a spatial frequency of about 3 c/deg (Campbell and Robson, 1968). Image motion and temporal flicker both alter visual sensitivity to contrast. Studies with gratings flickered in counterphase (e.g. Robson, 1966; Kelly, 1971) show that the form of the contrast sensitivity function is markedly changed by the temporal frequency at which spatial frequency components are flickered. In particular, gratings of low spatial frequency become more visible as their temporal frequency is increased, up to about 10 Hz. Here we examine the implications of the change of the form of the contrast sensitivity function for the visibility of drifting gratings of low spatial frequency and of moving bars of large size.

It is a commonly held assumption that the human visual system cannot resolve objects moving at high speeds (Dodge, 1900; Woodworth, 1906; Richards, 1969; Matin, 1974; Kelly, 1979a, b). As a typical example, Matin (1974) reports that although it has been shown that cat visual neurones respond to velocities of 100 deg/sec (e.g. Cleland *et al.*, 1971) "at least in the human visual system such velocities do not elicit a sensation that an object is moving" (p. 909). However, considering how widely this belief is held, and the fact that neurones in both the cat and monkey are capable of responding to very high velocities (e.g. Cleland *et al.*, 1971; Wurtz, 1969), there is surprisingly little psychophysical evidence to support it. Many early investigators observed that at speeds above 100 deg/sec, Landolt Cs or Snellen letters are not seen (e.g. di Silva, 1929). More recently Brown (1958) reported that a small spot of light is not visible

when it is moving faster than 32 deg/sec. On the other hand, Pollock (1953) and Johnstone and Riggs (1979), using larger test stimuli, have measured velocity thresholds more than an order of magnitude higher.

We measure contrast sensitivity to stimuli in rapid motion, firstly with periodic sinusoidal gratings caused to drift and secondly, with single biphasic bars consisting of one cycle of sinusoidal grating, caused to move. In all studies the observer is required to detect the direction of motion, not merely the presence of the stimulus on the screen. Thus it is motion rather than flicker thresholds which are measured.

PART 1: DRIFTING GRATINGS

In the first series of studies, we measured contrast sensitivity to sinusoidal gratings caused to drift at image speeds ranging from 0 to 800 deg/sec. To bring out more clearly the effect of image motion, each set of measurements was made at constant speed, rather than at constant temporal frequency which is more conventional (Robson, 1966; Van Ness *et al.*, 1967; Kelly, 1971). Thus, as we varied the spatial frequency F_s of the gratings, we varied also the temporal frequency F_t , so that the ratio F_t/F_s (i.e. the speed) remained constant.

Methods

Measurements were made both in Cambridge and Pisa. Computer generated gratings were suitably filtered and displayed on the face of a cathode ray oscilloscope at 150 frames/sec, 1000 lines/frame, using the standard television raster technique of Schade (1956). The visible screen was a circle of 20 cm diameter, centered within a 1 m² surround, floodlit to the same mean luminance as the screen (200 cd/m²). In order to encompass a wide range of spatial frequencies, viewing distance and hence field size of the screen was varied from session to session. Measurements within the velocity range of 0–1 deg/sec were

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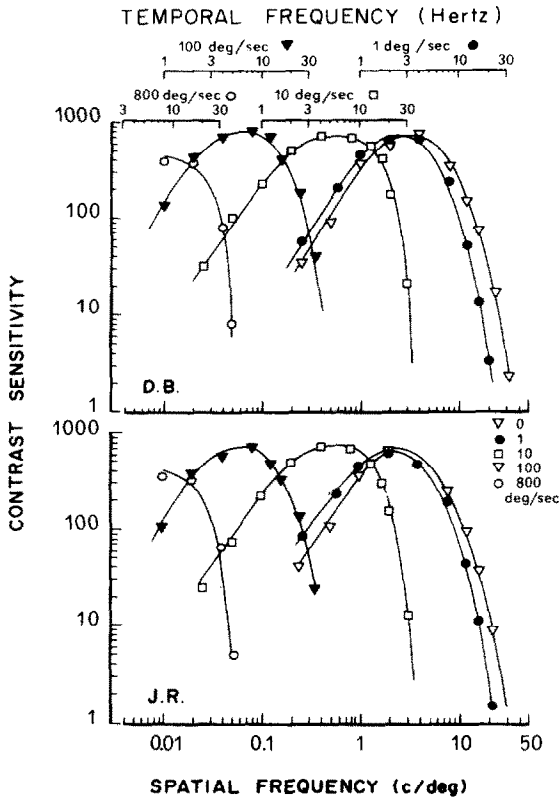


Fig. 1. Contrast sensitivity curves for the two observers for sinusoidal gratings drifting at various speeds. The lower abscissae shows the spatial frequency of the gratings, and the upper abscissae the corresponding temporal frequency for each drift speed. Note that at all drift speeds, the curves have the same height, width and general shape.

made at 70 cm (screen size 16 deg) and the remainder at 7 cm (screen size 110 deg)*.

Waveforms, and their positioning frame by frame, were provided by a small laboratory computer (PDP-8/1 for the Cambridge measurements and PDP-11/03 for the Pisa measurements), which also randomized trial conditions (including direction of drift) and recorded and averaged threshold measurements. Thresholds were determined by the method of adjustment, each data point being the mean of five separate settings. To minimize stereotyping of responses, the contrast was set before each trial to a random level unknown to the observer by a computer controlled logarithmic attenuator.

Gratings were vertical and drifted right or left, direction being randomized on each trial. Eye movements were minimized by instructing the observers to fixate a large (1 cm) black central fixation mark. Thresholds were set to the minimum contrast at which the direction of drift could be seen. Thus the curves reflect thresholds for motion detection, not

* Such close viewing distance will of course introduce considerable geometric distortions of the display but this should not significantly affect the form of the results (see also Fig. 5).

flicker-fusion. However, it should be noted that the thresholds for flicker do not differ greatly from those for motion in these conditions, as one would expect from the similarity in thresholds of drifting and counterphased gratings (Levinson and Sekular, 1975; Watson *et al.*, 1980).

Results are reported for two observers, the authors. Viewing was monocular, with the left eye patched.

Results and discussion

Threshold measurements for five different drift speeds are summarized in Fig. 1. The curves all have the same general form. The height is in each instance about the same, indicating the same peak sensitivity at all velocities, and all curves have the same general width, with similar low frequency and high frequency attenuation. What changes with drift speed is the position of the curves on the spatial frequency axis: the higher the velocity, the lower the spatial frequency at which the curves peak. At a velocity of 100 deg/sec, the curves peak at about 0.06 c/deg; and at this frequency, sensitivity is as high as it is for a stationary grating of 3 c/deg. Thus, a grating which is visible only at high contrast when the image is still becomes visible at minimal contrast when the image moves at the correct velocity.

The upper abscissa of Fig. 1 shows the temporal frequency (i.e. the rate at which the grating bars pass a given point) associated with each spatial frequency and velocity ($F_t = F_s \cdot v$). From these axes it can be seen that the temporal envelope varies little with drift speed. Figure 2 depicts this consistency more clearly, by plotting the same data on axes of temporal rather than spatial frequency. Whereas the peaks of the spatial curves of Fig. 1 spread over a range of about three logarithmic units, the peaks of the temporal curves of Fig. 2 are nearly coincident, varying by only about a half of a logarithmic unit. It is only at the lowest velocity, 1 deg/sec, that there is a small peak shift, and here the results may have been influenced by small eye movements (*cf.* Kelly, 1979a, b).

At every velocity measured in this experiment, the upper limit for motion perception is set by the temporal frequency of image modulation. Velocity itself is

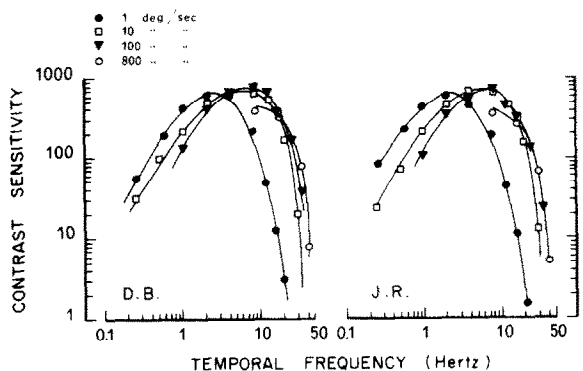


Fig. 2. The same measurements as Fig. 1 plotted against temporal rather than spatial frequency.

irrelevant. The form of the curves of Fig. 2 suggests that signals from moving patterns are all passed through temporal filters of roughly the same shape, and that motion can be perceived provided that the limits of the temporal filters are not exceeded. But, as Fig. 1 shows, the associated spatial filters must encompass an enormous range, extending far further down the spatial frequency spectrum than most investigators care to go; and when stimuli of these very low spatial frequencies are moving so as to modulate at their optimal temporal frequency, they are moving very fast indeed.

The consistency of the form of the curves of Fig. 2 is interestingly reflected in the fact that the very fast velocities never appear particularly fast. At 800 deg/sec (and in fact even at velocities as high as 3000 deg/sec), a low frequency grating of modest temporal frequency appears to glide past the field of view smoothly and unhurriedly. And, at all temporal frequencies, the apparent speed remains unchanged with viewing distance, which alters both spatial frequency and velocity but leaves temporal frequency unchanged. These observations suggest that perceived velocity is computed from the temporal frequency of signal modulation, not retinal velocity, thereby maintaining velocity constancy over a wide range of viewing conditions. This point requires further investigation.

PART 2: MOVING BARS

The results of Part 1 show that image motion, no matter how swift (within rather broad experimental limits), does not impair sensitivity to gratings but merely changes the frequency spectrum to which the visual system responds, in effect sliding the window of visibility to a lower position on the spatial frequency axis, without changing its form. Motion has two effects: it deemphasizes or "smears" high frequency components, but also emphasizes low spatial frequency image components, that is components of large size, which are virtually invisible when the image is still.

It might be thought that the low frequency results do not extend to single objects, as gratings have an unlimited number of cycles moving past the retina at a steady flicker rate. And, as previously mentioned, it is widely believed that object motion is invisible at image velocities above 100 deg/sec. Therefore, we considered the visibility of objects: single cycles of bars of grating as they move in isolation across a screen of the same mean luminance as the bar itself.

Methods

Single vertical bars, comprising one cycle of sine wave grating starting at zero phase, were displayed on the face of a cathode ray oscilloscope at 1000 frames/sec with free running 3 MHz vertical raster. The visible screen was a 5×5 cm square of mean luminance 20 cd/m^2 , with a central black fixation mark of

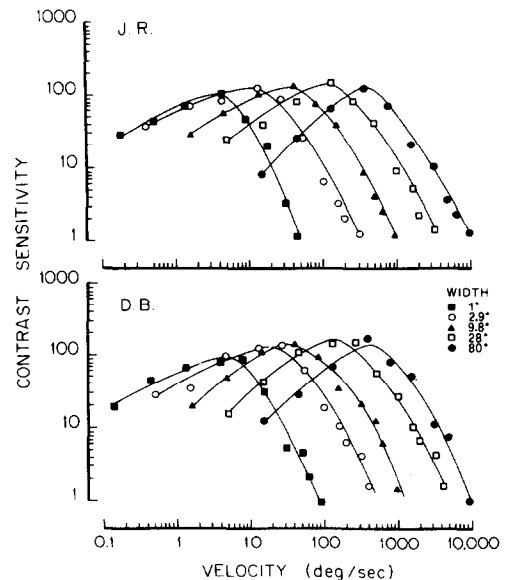


Fig. 3. Contrast sensitivity to single cycle, biphasic sinusoidal bars of various width as a function of image velocity.

5 mm diameter. To encompass a wide range of bar widths, viewing distance (and hence field size of the screen) was varied from session to session, over a range from 3 cm to 3 m. At the nearer viewing distances, the image was brought into focus by a positive lens. All viewing was monocular with left eye patched. Each bar was formed by a function generator (Interstate Electronic Corporation F34), triggered by computer (PDP 11-03) at a suitable delay after the start of each frame. The delay could be incremented or decremented by the computer (equipped with a 1 MHz digital clock) so as to cause the bar to be slightly displaced on each frame, and hence to appear to move smoothly either rightwards or leftwards across the screen at any desired velocity. Step size was sufficiently small in relation to bar width for motion to remain smooth in appearance even at the highest velocities. It also meant that the time averaged luminance across the screen was almost constant, the biphasic bar leaving no visible aftertrace. After the passage of each bar, there was a 0.5 sec pause before a new bar appeared.

As before, thresholds were determined by method of adjustment, but key data points were checked with forced choice methods. Threshold was defined as the minimum contrast at which the direction of the motion of the bar could be seen. Velocity was calculated at the point of fixation, and applies strictly only at this point, since the distortions resulting from a flat screen are not negligible at the closest viewing distance.

Results and discussion

Threshold measurements for five bar widths are summarized in Fig. 3, as a function of image speed.

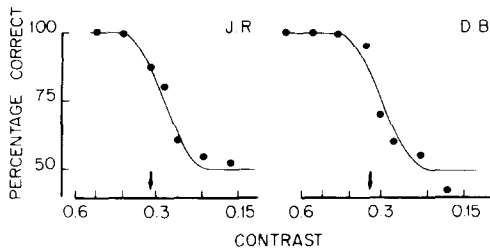


Fig. 4. Forced choice measurements to confirm the visibility of bars moving at 10,000 deg/sec. The two observers were required to report the direction of motion (rightward or leftward drift) of a bar of width 80 caused to move at 10,000 deg/sec (viewing distance 3 cms). Each point is the average of 40 trials, collected over four brief sessions. The computer randomized the conditions (including direction of drift), presented the trials and scored and averaged the response. The arrows point to thresholds for the two observers, corresponding to the 83% correct response.

All curves have comparable peak values, indicating comparable sensitivity at best velocity for all bar widths. However, the shape of the curves changes systematically with bar width, having a somewhat shallower low velocity cut at smaller bar widths.

The most significant feature of the data is that, as bar width increases, the velocity at which sensitivity peaks also increases. For the widest bar (80 deg) the velocity peak is to be found in the range of 300–500 deg/sec, well above the value of 100 deg/sec, which is often taken to be the limiting value for the perception of objects in motion. However, bars which are 1 deg wide are invisible at any contrast when moving at speeds in excess of 100 deg/sec.

Forced choice measurements. The widest bar is easily visible, at high contrast, when moving at 10,000 deg/sec. To confirm that objects are in fact visible at these velocities, this last point of the curve for the 80 deg bar was checked by a two alternative forced choice method, in which the observer was required to report the direction of motion of the bar, which moved, on each trial, either left or right at random. The results, summarized in Fig. 4, show that the method of adjustment measurements are if anything conservative, as the forced choice thresholds for seeing the direction of motion (2.8 and 3.5 for D.B. and J.R. respectively at 83% correct) are slightly higher than those of Fig. 4 (both being 1).

A reviewer has raised the possibility that observers may have been tracking the moving stimuli, thereby reducing the retinal image velocity, which would of course trivialize our results. While eye tracking may be possible (but not probable, given the heavy fixation mark) for the measurements of Fig. 1 where the stimulus was continuously visible, it is not possible under these conditions of brief stimulus presentation. For each trial the whole display was completed by 16 msec, well within the latency for pursuit eye movements (Westheimer, 1954).

Effect of viewing distance. The scrupulous reader might raise several objections at this point. Firstly, because of the flat screen, there is considerable variation in angular velocity across the screen at the closer viewing distances. Secondly, the distance traversed by the bar is short in comparison to the width of the bar (about one bar width) and the time for which the bar is visible varies inversely with velocity at each viewing distance. To investigate these possible sources of perturbation, we remeasured visibility thresholds for the 28 deg bar at two viewing distances, 3 and 10 cm, using the same 5 cm square mask for the oscilloscope face. Thus at 10 cm, the bar size was 5 cm, 28 deg, and the field size 28 deg, while at 3 cm the bar size was 1.5 cm, 28 deg, and the field size 80 deg. At this closer viewing distance, the bar moved for about three times as long as for the further distance.

Figure 5 summarizes the results. The close agreement between the two curves obtained at different distances suggests that neither size and velocity distortions resulting from the flat screen, nor variability in the duration of the motion trajectory materially distort the form of the data. The slight differences between the curves can probably be put down to probability summation which works in favour of the bar that moves over the longer path (Sachs *et al.*, 1971; Watson, 1979).

The results of this section are quite consistent with those of Part 1. For example, consider the results of the 80 deg bar (Fig. 3). An 80 deg bar has a fundamen-

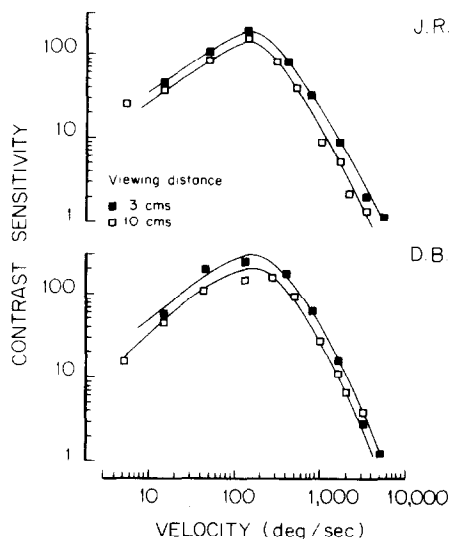


Fig. 5. Contrast thresholds for a 28 deg moving bar at two viewing distances, 3 and 10 cm, and hence two different field widths, 80 and 28 deg respectively. The bar traversed a distance equal to about three bar widths at the close viewing distance, but only about one bar width at the farther viewing distance. The close agreement of the two curves suggests that neither geometrical distortions resulting from a flat screen and close viewing distance, nor extent of excursion of the target alter significantly the form of the results.

tal frequency of 0.0125 c/deg. Thus the peak velocity for this bar, 300–500 deg/sec, corresponds to a temporal frequency of about 6 Hz for the fundamental, in agreement with the curves of Fig. 2 (small discrepancies between these results can probably be accounted for by the difference in mean luminance for the two sets of measurements). Spatial frequency components are visible up to temporal frequencies of 50 Hz. At an image speed of 10,000 deg/sec (when the 80 deg bar is just visible) only those components of 0.005 c/deg and below will be visible. However, a single bar has a wide spread of spatial components including some at much lower frequencies than the fundamental*. Thus the 80 deg bar comprises not only its fundamental of 0.0125 c/deg, but also components of much lower spatial frequency (extending below 0.005 c/deg) which, even at image speeds of 10,000 deg/sec, modulate at temporal frequencies below 50 Hz. These low spatial frequency components presumably render the bar visible at high velocities.

GENERAL DISCUSSION

It is well established, and now widely understood, that stationary scenes, observed in good light with the resting eye, are seen through a "spatial frequency window". It has been assumed that motion lowers and narrows the visual passband. For example, Kelly (1979) says: "at velocities greater than 100 deg/sec there would be no contrast sensitivity at any spatial frequency within the range of normal vision" (p. 1344). We have shown that image motion does not alter the band pass characteristics of vision, neither by lowering maximum sensitivity, nor by narrowing the band itself. Rather, the effect of image motion is to slide the spatial frequency window down the spatial frequency scale, diminishing neither its height nor its width. Sensitivity is maintained, and so too is the range of visible spatial frequencies.

Part 2 shows that the visibility objects in motion may be understood in terms of the visibility of their spatial frequency components. The direction of motion of large objects, which contain low spatial frequency components, can be resolved at high velocities at which smaller objects are invisible. For example, a bar 1 deg in width becomes invisible at 100 deg/sec however high its contrast, but wider bars are easily seen at this velocity.

All thresholds reported here are *motion thresholds*, the minimum contrast required to see the direction of motion. At threshold, one seems to have a pure sensation of motion, that is objectless motion (Wertheimer,

1912) with no clear impression of what it is that is moving (Keeseey, 1972; Kulikowski and Tolhurst, 1973). However, at all spatial frequencies and at all bar widths employed in these experiments, it was necessary to raise the contrast by only a few decibels above the threshold for pure motion in order to see clearly the spatial structure of the grating or the form of the sinusoidal bar. This casts some doubt upon the popular notion that there are two independent visual systems spanning different spatial frequency ranges, one analyzing pattern and the other motion (e.g. Tolhurst, 1973; Kulikowski and Tolhurst, 1973; Kulikowski, 1978). Gratings of spatial frequency 0.01 c/deg, an order of magnitude below the supposed lower limit of the pattern system (e.g. Tolhurst, 1973), have a clear spatial structure at appropriate drift speeds, even at low contrast. It seems more probable that the detectors which respond to these low frequencies are organized so as to signal both pattern and motion (Burr, 1979, 1980, 1981; Lennie, 1980; Derrington and Henning, 1981).

Image velocities in excess of 100 deg/sec are the usual result of saccadic eye movements, which occur frequently in natural viewing. Much speculation on the problem of *saccadic suppression*, or *saccadic omission* (failure to see a visual grey out) has supposed that saccadic speeds are too fast for the visual system to resolve and therefore result in a complete blurring or "grey out" of the visual scene (e.g. Dodge, 1905; Woodworth, 1938; MacKay, 1973; Campbell and Wurzt, 1978). However, most previous measurements of vision during saccades have employed targets of high spatial frequency or small size, which, as our results show, will be rendered invisible at saccadic velocities. On the other hand, low spatial frequency components, not easily visible when the image is stationary, are made more visible and can readily be resolved when the image moves at saccadic speeds. Why then is the observer not startled during a saccade by the sudden intrusion of low frequency components onto the scene? A subsequent study suggests that during saccades motion sensitivity is dampened, precisely to avoid the disturbing consequences of saccadic image motion which would follow if it were left intact (Burr *et al.*, 1981).

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* The spectrum of spatial frequencies ($F(w)$) of a single cycle of sine wave is given by:

$$F(w) = \frac{Aw_0}{\pi} \frac{1}{w_0^2 - w^2} \sin \frac{2\pi w}{w_0}$$

where A is the amplitude, and w the fundamental spatial frequency of the single cycle.

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