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Sensitivity to Second-order Motion as a Function of Temporal Frequency and Eccentricity

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There is considerable evidence that second-order motion, such as motion consisting of a drifting contrast modulation, is detected separately from first-order motion. Some previous studies have shown that the rate at which sensitivity declines as either drift speed or eccentricity increases is the same for both types of motion. However, these studies have used second-order motion stimuli based on static noise carriers, which we have shown (Smith & Ledgeway, 1997) may be inappropriate because they can give rise to local first-order artifacts. By using dynamic noise carriers, we isolate the second-order motion mechanism and show that its temporal response is much worse than that of the first-order system but that its rate of sensitivity loss with increasing stimulus eccentricity is indeed similar to that of the first-order motion system. © 1998 Elsevier Science Ltd. All rights reserved.

Motion Eccentricity Second-order motion Temporal frequency

INTRODUCTION

Image motion may be defined either in terms of spatiotemporal variations in luminance, a first-order property of the image, or in terms of spatiotemporal variations in any of a variety of second-order properties, such as contrast. It has been known for some time that some types of second-order motion are visible to the human observer. Badcock & Derrington (1985) (Derrington & Badcock, 1985) suggested that second-order motion is detected by a different system from that which detects first-order motion. Since then, a variety of authors have presented evidence for separate detection of the two types of motion (see Smith, 1994 for a review) and computational strategies for detecting second-order motion have been developed (Chubb & Sperling, 1988; Wilson, Ferrera, & Yo, 1992). Both types of motion are found in natural scenes containing motion and normally the two can be expected to be correlated. Presumably, detecting both types and integrating the two motion estimates increases the accuracy of the final motion signal to an extent that justifies the additional computational load.

This study focuses on two aspects of sensitivity to second-order motion. The first is temporal sensitivity. Derrington, Badcock, & Henning (1993) found that direction detection for second-order motion stimuli is impossible at stimulus durations below about 200 msec, suggesting that the temporal resolution of the second-order motion system may be significantly worse than that of the first-order system. Since then, Holliday & Anderson (1994), Derrington (1994) and Lu & Sperling (1995) have all plotted temporal contrast sensitivity functions for second-order motion and compared them with those for first-order motion. Holliday and Anderson measured direction thresholds for drifting beats of various speeds. They obtained a low-pass temporal contrast sensitivity function with a notch at about 6 Hz which led them to interpret the function as the envelope of two different mechanisms. Overall, temporal acuity (the highest detectable drift temporal frequency) was as good as for first-order motion. Derrington used amplitude-modulated gratings and found that sensitivity to a drifting contrast envelope falls off more rapidly as temporal frequency increases than does sensitivity to first-order motion, provided a low-contrast carrier is used. With a high-contrast carrier he found sensitivity functions which were similar to those for first-order motion and he interpreted these in terms of the presence of a distortion product arising from a brightness nonlinearity. When beats are used, as in Holliday and Anderson's study, the contrast of the carrier is varied to find the threshold and so high carrier contrasts are needed at high temporal frequencies. Derrington's result is therefore consistent with Holliday and Anderson's notion that their sensitivity function reflects the envelope of a low-pass, low-acuity second-order mechanism and sensitivity to a (first-order) distortion product at high frequencies. However, Lu and Sperling used a quite different stimulus (contrast-modulated two-dimensional

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static noise) and also found that temporal acuity was as good for second-order as first-order. Indeed, their temporal contrast sensitivity functions were very similar to those for first-order motion in all respects. Thus, the temporal sensitivity of the second-order motion system is left unresolved.

With respect to the experiments of Lu & Sperling (1995), we have recently reported (Smith & Ledgeway, 1997) that contrast-modulated static noise may not be an appropriate stimulus for the study of second-order motion thresholds because it can give rise to local first-order artifacts upon which detection can be based, particularly when large noise pixels are used. We have shown that when a dynamic noise carrier is used, the psychophysical results obtained are qualitatively different from those obtained with static noise carriers, even though the two are equivalent in terms of the analysis of Chubb & Sperling (1988) and neither should support first-order motion. When dynamic noise is used, thresholds for identifying the direction of motion of a drifting contrast envelope are much higher than those for detecting its orientation. When static noise is used, the two thresholds are the same, as they are for first-order motion (Green, 1983; Watson, Thompson, Murphy, & Nachmias, 1980). In addition, different patterns of dependence on carrier contrast and noise pixel size are found for the two carriers.

Our interpretation of these psychophysical results was that the threshold differences reflect the involvement of the first-order system in the case of static but not dynamic carriers and that this arises because of the presence in the stimulus of local first-order motion artifacts. A full description and discussion of these local artifacts is given in Smith & Ledgeway (1997). Briefly, binary noise patterns contain local stochastic biases in the proportion of light and dark pixels. When the noise is multiplied by a drifting envelope to create second-order motion, these luminance biases are expected to give rise to local first-order motion signals which have the same direction and speed as the envelope. Such signals tend to sum to zero over the entire image, but are detectable locally. This type of first-order artifact is quite different from the better-known global distortion products that arise from luminance non-linearities.

In view of these findings, the possibility arises that Lu & Sperling (1995) may inadvertently have measured sensitivity to local first-order motion artifacts rather than to second-order motion *per se*, explaining why they obtained similar functions for both. In the present paper, we present measurements of sensitivity to second-order motion using contrast-modulated dynamic two-dimensional noise as the carrier. We find that temporal contrast sensitivity is quite different from that found with first-order motion, being low-pass for temporal frequency and declining rapidly as temporal frequency increases.

The second aspect of sensitivity to second-order motion which we examine is the effect of eccentricity on sensitivity. This has previously been examined by Pantle (1992), Smith, Hess & Baker (1994) and Solomon & Sperling (1995). Pantle reported that the direction of motion of a variety of second-order motion patterns is invisible in the periphery, even though second-order spatial structure may be visible. Smith *et al.* reported that sensitivity to second-order motion falls off with eccentricity at the same rate as that for first-order motion. However, Smith *et al.* used contrast-modulated static noise and so their results are questionable on the same grounds as those of Lu & Sperling (1995). It is shown here that the data of Smith *et al.* (1994) probably do indeed reflect the detection of first-order artifacts, but that when these are removed to isolate the second-order motion mechanism, sensitivity is still found to fall off with eccentricity at a rate similar to that found for first-order motion.

GENERAL METHODS

Subjects

Two subjects were used. Both were experienced observers who were naïve to the purpose of the experiments and were paid for their time.

Stimuli

All stimuli were contrast-modulated 2-D noise patterns. They were generated using a Matrox image processing system and were displayed on a monochrome monitor with P4 (white) phosphor at a refresh rate of 67 Hz. The mean luminance was 38 cd/m^2. The carrier was either static or dynamic spatially broadband noise. Noise was generated simply by assigning one of two states, light or dark, at random to each pixel. The noise pixel size was either 2.4 or 6.0 min arc. In the case of static noise, the same noise sample was used throughout the image sequence; in the case of dynamic noise a new sample was used on each frame. The contrast modulation of the carrier was achieved by multiplying it by a modulating waveform. This was done in real time using a double-entry look-up table. The contrast modulation was always a raised sinusoid whose amplitude was shaped in space by a 2-D gaussian. This produced a 2-D Gabor patch whose amplitude (modulation depth) could be varied to find a threshold by varying the amplitude of the sinusoid. The position of the gaussian envelope remained unchanged over time, while the phase of the grating within it was updated to produce motion. Contrast modulations were also shaped in time, by varying the amplitude of the modulating waveform prior to multiplication by the carrier. Each animation sequence lasted 750 msec. The grating (envelope) amplitude started at zero, was ramped up to some peak value with an integrated gaussian waveform over the first 255 msec, remained constant at that level for 240 msec and was then ramped down again to zero over 255 msec. Thus, the carrier appeared abruptly and had a constant mean (space-average) contrast over time but the amplitude of the contrast envelope was shaped in time.

Viewing was binocular. All images subtended

4 deg × 4 deg at the viewing distance of 95 cm and were presented on a uniform background of the same mean luminance. They were carefully gamma-corrected (using a look-up table) to minimize distortion products arising in the screen. Precautions were taken to minimize changes in the gamma characteristics of the monitor over time (long warm-up period prior to commencement of experimental sessions, cushioned mounting of the monitor to reduce vibration) and the correction factor was checked regularly. Inevitably, small screen non-linearities survived these procedures, but we have shown (Smith & Ledgeway, 1997, Fig. 11) that modest errors generate distortion products that are too small to mediate detection, at least for this class of images.

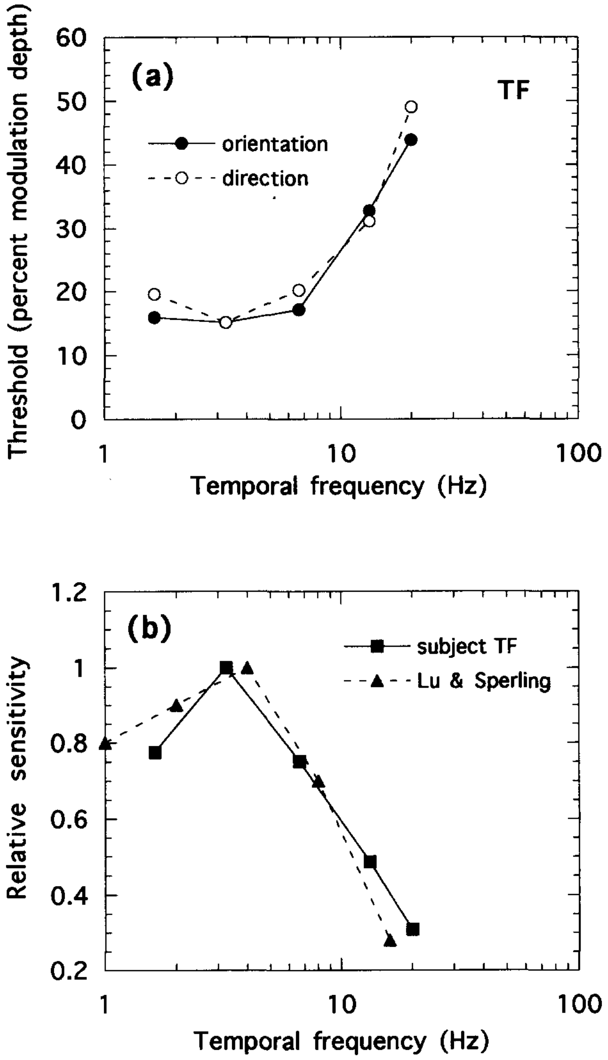

FIGURE 1. (a) Thresholds for detecting the orientation and the direction of a drifting contrast modulation, as a function of drift temporal frequency. The carrier was static two-dimensional (2-D) noise and the envelope spatial frequency was 2.5 c/deg. (b) The direction thresholds shown in (a) expressed in terms of relative sensitivity, in the manner of Lu & Sperling (1995), calculated by expressing each threshold as the ratio of the lowest threshold obtained at any frequency to the threshold at the frequency in question (squares). Also shown (triangles) are the results obtained in a comparable experiment by Lu & Sperling (Fig. 7; subject ZL).

Procedure

Two detection thresholds were measured simultaneously using the method of constant stimuli. These were the contrast modulation depth required to detect the orientation of the grating patch and that required to detect its drift direction. The subject fixated the centre of the screen. Each experimental run commenced with a 30 sec period during which the screen was uniform. In each trial the subject was presented with a single animation sequence of the same mean luminance as the uniform field. The orientation of the drifting contrast modulation could be either horizontal or vertical and it could be drifting in either direction along the axis orthogonal to its orientation. These parameters were determined at random with equal probability. At the end of the trial the image was replaced by a uniform screen. After an interval of at least 3 sec the next trial was presented. After each trial the subject was required to make two forced-choice responses. The first response was the orientation of the modulation and the second was its direction. The computer recorded all responses in terms of whether they were correct or incorrect. There were 50 trials in each run, ten at each of five modulation depths chosen on the basis of pilot trials so as to span the orientation and direction detection thresholds. Five identical runs of 100 trials were completed for each experimental condition so as to give a total of 50 responses at each modulation depth (250 responses in total). A sigmoid, constrained to asymptote at 50% and 100%, was fitted to the function relating per cent correct responses to modulation depth using a least-squares method. The midpoint on this curve (75% correct performance) was taken as the threshold for that condition. Separate functions were fitted to the orientation and direction data to yield two separate threshold values, each based on 250 responses.

EXPERIMENT 1: TEMPORAL SENSITIVITY

Initially we replicated the results of Experiment 1 of Lu & Sperling (1995), for contrast-modulated static noise, using a single subject. The task employed by Lu and Sperling was a direction discrimination task similar to one of our two simultaneous tasks described above. To match our stimuli to theirs as closely as possible, we used a static noise carrier of pixel size 2.4 min arc, a carrier contrast of 50% and an envelope spatial frequency of 2.5 c/deg. For completeness, we obtained orientation as well as direction judgements. Five drift temporal frequencies were used, ranging from 1.3 to 20 Hz. The results of this preliminary experiment are shown, expressed both in terms of orientation/direction thresholds and as normalized sensitivity based on the direction thresholds, in Fig. 1. The sensitivity function is in close agreement with that obtained by Lu and Sperling.

Having successfully replicated the temporal sensitivity profile obtained by Lu and Sperling, we then proceeded to investigate the role of local first-order artifacts. It is clear from Fig. 1 that the thresholds obtained in our initial experiment were similar for orientation and direction. Consequently, we suspected that the results of Lu and

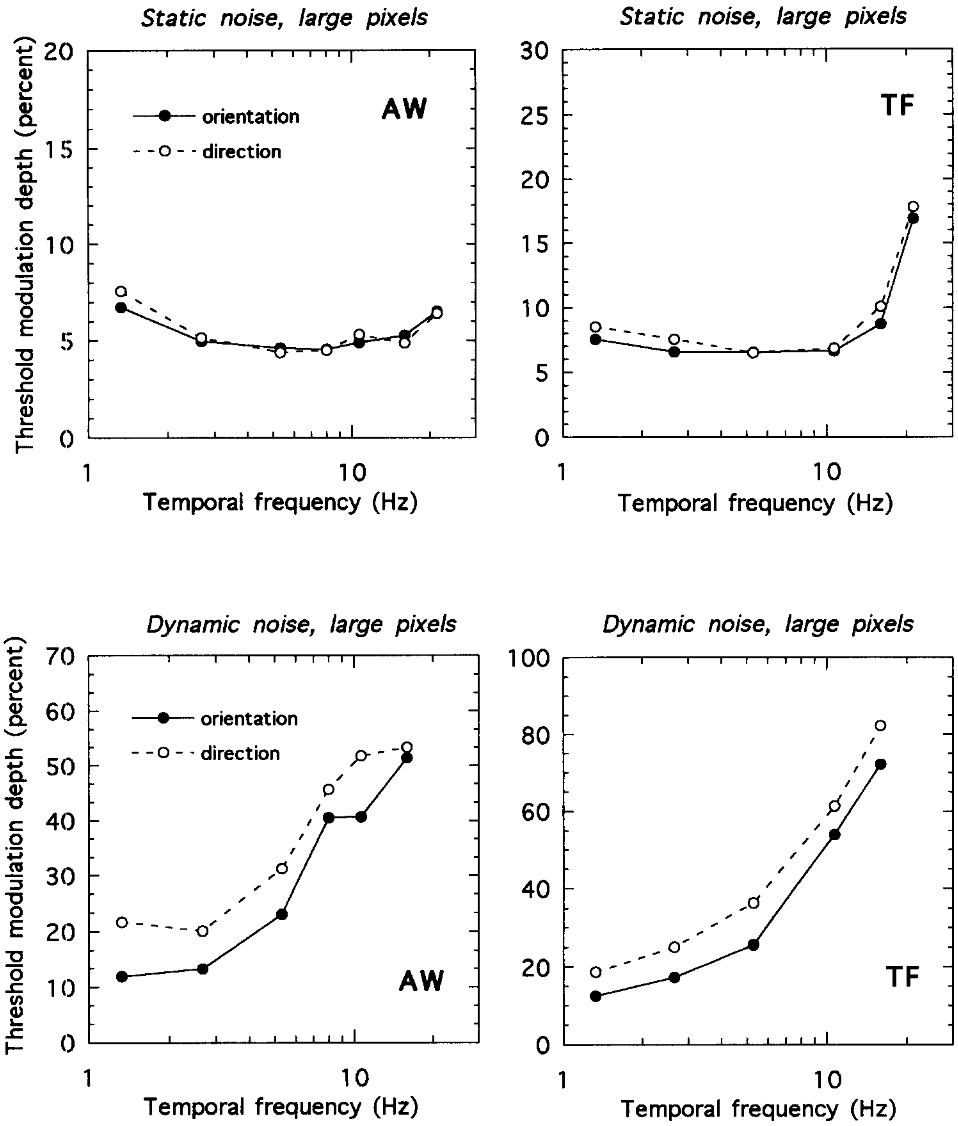

FIGURE 2. Thresholds for detecting the orientation and the direction of a drifting contrast modulation, as a function of drift temporal frequency. In all cases the spatial frequency of the contrast envelope was 1 c/deg. The carrier was either static 2-D noise (upper panels) or dynamic 2-D noise (lower panels) and the size of the noise pixels was 6 min arc. Results for two subjects are shown separately.

Sperling reflect the involvement of local first-order artifacts of the type described in the Introduction and so do not provide a reliable estimate of sensitivity to drifting contrast modulations.

We therefore repeated our experiments using a dynamic noise carrier. We found that when dynamic noise is used, eliminating local first-order artifacts, it is extremely difficult to detect an envelope of spatial frequency 2.5 c/deg at any drift speed. We therefore used an envelope spatial frequency of 1 c/deg. Thresholds for orientation and direction were measured using both static and dynamic carriers. Two check sizes were used. One was 6 min arc (corresponding to 5 screen pixels), chosen because it gives a ratio of envelope frequency to check size similar to that used by Lu and Sperling. However, the use of such large noise pixels exacerbates the problem of local first-order components (see Smith & Ledgeway, 1997) and so a smaller check size of 2.4 min arc (two screen pixels) was also used. The carrier contrast was again 50%.

Results and discussion

Figure 2 shows, for two subjects, results obtained for both static and dynamic noise carriers using a noise pixel size of 6 min. In the case of static noise, thresholds are in the range 5–20% over the range of temporal frequencies tested. They are lowest for medium drift temporal frequencies and thresholds for orientation and direction are very similar. In the case of dynamic noise, a rather different pattern of results is evident. Thresholds are higher than for static noise. They are lowest not at medium frequencies but at the lowest frequencies and they rise sharply as drift temporal frequency increases. Thresholds for direction are consistently higher than those for orientation.

Figure 3 shows results obtained with a noise pixel size of 2.4 min. In the case of dynamic noise carriers (lower

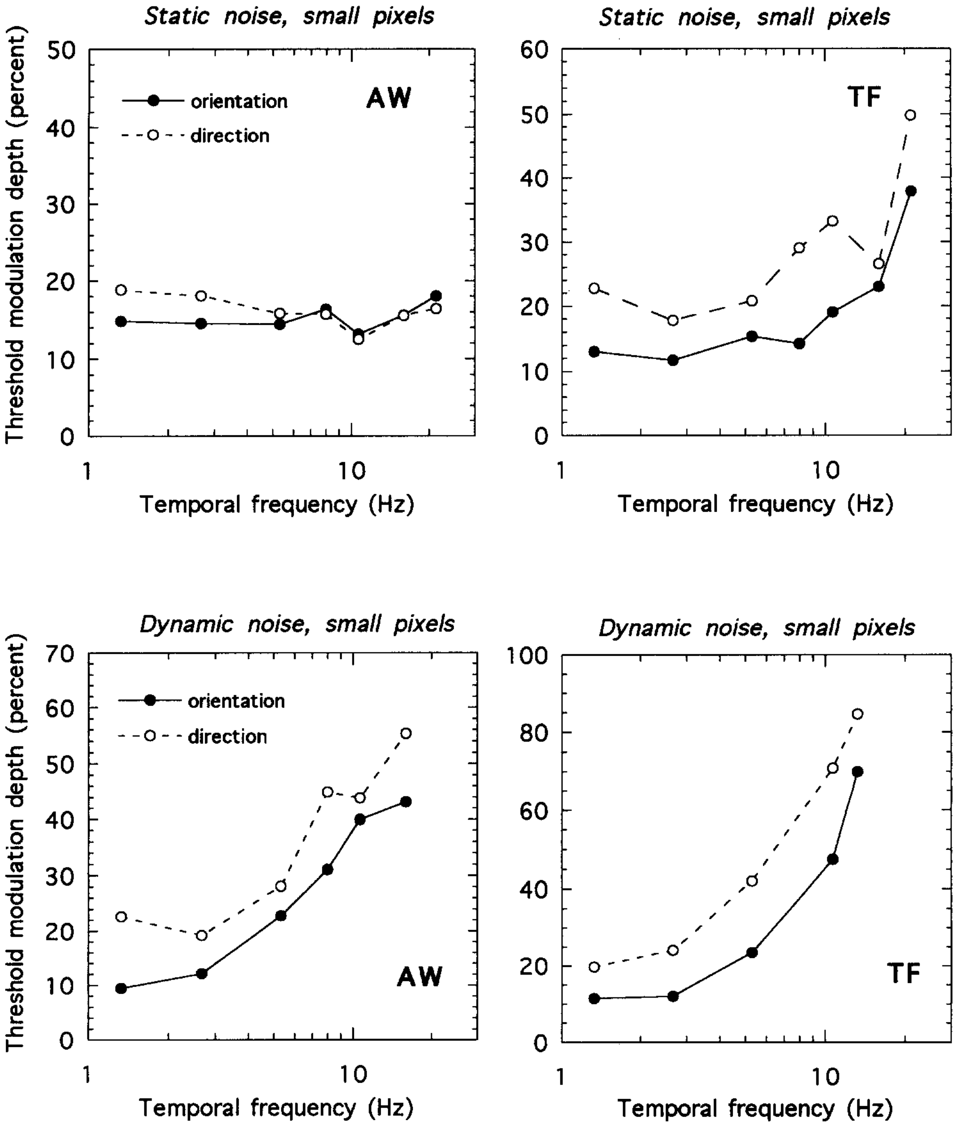

FIGURE 3. Thresholds for detecting the orientation and the direction of a drifting contrast modulation, as a function of drift temporal frequency. All details are the same as for Fig. 2 except that the size of the noise pixels was 2.4 min arc.

plots), the results are very similar to those found with larger noise pixels (Fig. 2). In the case of static noise, thresholds are rather higher than with larger pixels and there is a tendency for direction thresholds to be higher than orientation, particularly for subject TF. In the case of TF, thresholds rise sharply with temporal frequency and the functions resemble those for dynamic noise.

As previously stated, we regard a difference between orientation and direction thresholds as the hallmark of detection by a true second-order motion mechanism. Where this difference is evident (for dynamic noise in all cases and for static noise with small pixels in the case of TF) the threshold functions rise steeply with increasing temporal frequency. Where there is no clear difference, the functions have a different shape, being flatter and rising less steeply at high temporal frequencies. In these cases we believe that detection is based on local first-order artifacts that arise from the use of static noise. In the case of TF, static noise, small pixels, it appears that the second-order system is more sensitive to contrast modulation than the first-order system is to the luminance artifacts; in all other static noise cases the reverse is true.

Figure 4 shows the results for the direction task for all four combinations of static/dynamic noise and large/small pixels, expressed in terms of relative sensitivity. For subject AW, the two functions obtained using static noise resemble the conventional (first-order) temporal contrast sensitivity function, peaking at about 8 Hz. The function is different from that in Fig. 1, which peaks at a lower frequency and declines more sharply at higher frequencies. Since the only difference between the two experiments is envelope spatial frequency, we attribute this difference to the known effects of spatial frequency on temporal sensitivity (e.g. Robson, 1966; Kelly, 1979). The two sensitivity functions obtained with dynamic noise have a quite different shape. Sensitivity is best at the lowest drift temporal frequencies and declines sharply as frequency is increased. We argue that these low-pass functions reflect the true sensitivity of the second-order

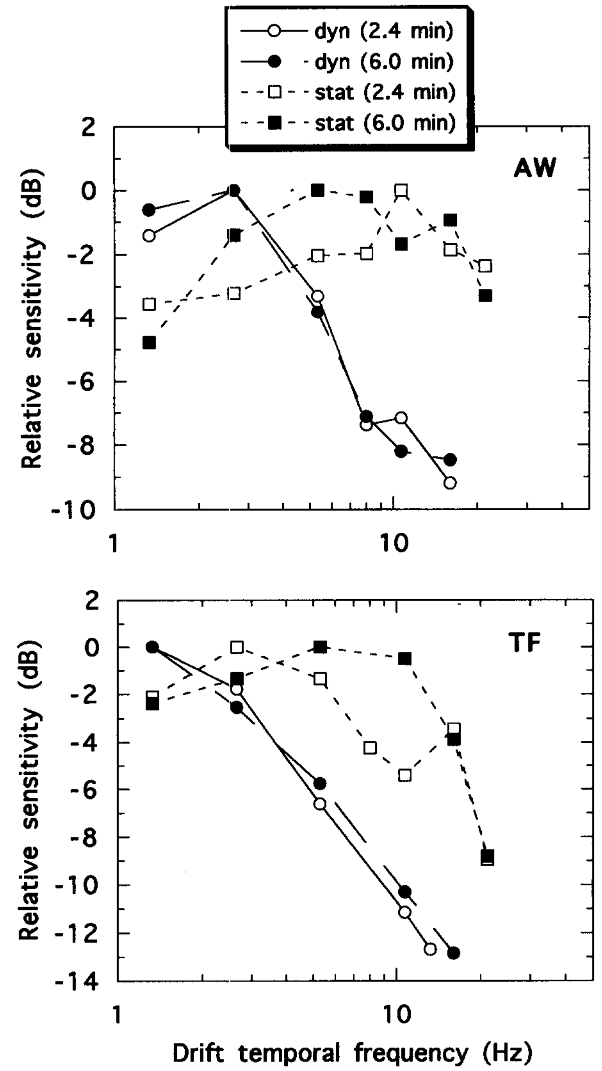

FIGURE 4. Temporal contrast sensitivity functions derived from the thresholds shown in Figs 2 and 3. For each function, sensitivity is expressed in dB, where 0 dB is the sensitivity at the most sensitive frequency on that function. For comparison with Fig. 1, note that 14 dB corresponds to a sensitivity ratio of 0.2. Sensitivity functions are shown separately for the two subjects. Key: circles, dynamic noise carrier; squares, static noise carrier; filled symbols, large noise pixels; open symbols, small noise pixels.

motion system. The results for subject TF are similar. However, the function obtained with static noise and small pixels is intermediate between the two types. It appears that this subject may have been using first-order cues in some cases and second-order cues in others, whereas for the large-pixel case (static noise) she consistently used first-order artifacts. A similar notched function is apparent in the temporal sensitivity data obtained by Holliday & Anderson (1994) with beats. It seems likely that their functions also reflect the envelope of a low-pass second-order system and a bandpass first-order system.

EXPERIMENT 2: EFFECT OF ECCENTRICITY

In order to compare the rate at which sensitivity declines with stimulus eccentricity for first- and second-order motion, we conducted experiments of a very similar nature to those in Experiment 1 but using eccentric fixation. A set of fixation points was marked on a white card which surrounded the display. These points fell on a line inclined at 45 deg leading up and left from the centre of the display. Thus, the image was always presented in the lower-right quadrant of the visual field. This arrangement ensured that the task was minimally affected by any difference in sensitivity among the four directions used, particularly those due to differences between foveofugal and foveopetal motion (e.g. Georgeson & Harris, 1978; Albright, 1989). In addition, this arrangement avoids the blindspot in both eyes.

The results of Experiment 1 are in line with the conclusion of Smith & Ledgeway (1997) that the use of static noise carriers can result in first-order artifacts and so yields measures of first-order sensitivity, whereas the use of dynamic noise yields true measures of sensitivity to contrast modulations. In Experiment 2 we used both types of carrier and compared the results, as was done in the case of temporal frequency in Experiment 1. Thus, sensitivity to first- and second-order motion was compared as a function of eccentricity. The noise pixel size used was 2.4 min for dynamic noise and 6 min for static noise. This difference was introduced because small checks help to avoid luminance-based detection while large checks facilitate it, ensuring that dynamic and static conditions isolate second- and first-order mechanisms, respectively. The spatial frequency of the envelope was 1 c/deg and the contrast of the carrier was 21%. A fixed drift temporal frequency of 2.7 Hz was used. All other details were the same as in Experiment 1.

Results and discussion

Orientation and direction thresholds are shown as a function of stimulus eccentricity in Fig. 5. In all cases, thresholds rise with eccentricity, as expected. With dynamic noise carriers (reflecting sensitivity to second-order motion) direction thresholds are consistently higher than orientation thresholds, as in Experiment 1. The greatest eccentricity at which direction could be detected with 75% accuracy was 12 deg for subject AW and 8 deg for TF. In the case of static noise carriers, thresholds are lower and both subjects could easily detect direction at the highest eccentricity used (12 deg). The thresholds for orientation and direction are similar, although they diverge slightly at the highest eccentricities. Thus, it again appears that the data obtained with static noise reflect sensitivity to first-order motion, while those obtained with dynamic noise reflect sensitivity to second-order motion. First-order motion direction is visible at greater eccentricities than second-order, in line with previous assertions (Pantle, 1992; Smith *et al.*, 1994).

However, to say that first-order motion is visible at greater eccentricities than second-order motion is not the same as saying that second-order motion sensitivity declines more rapidly with eccentricity than does first-order sensitivity. This is because second-order sensitivity

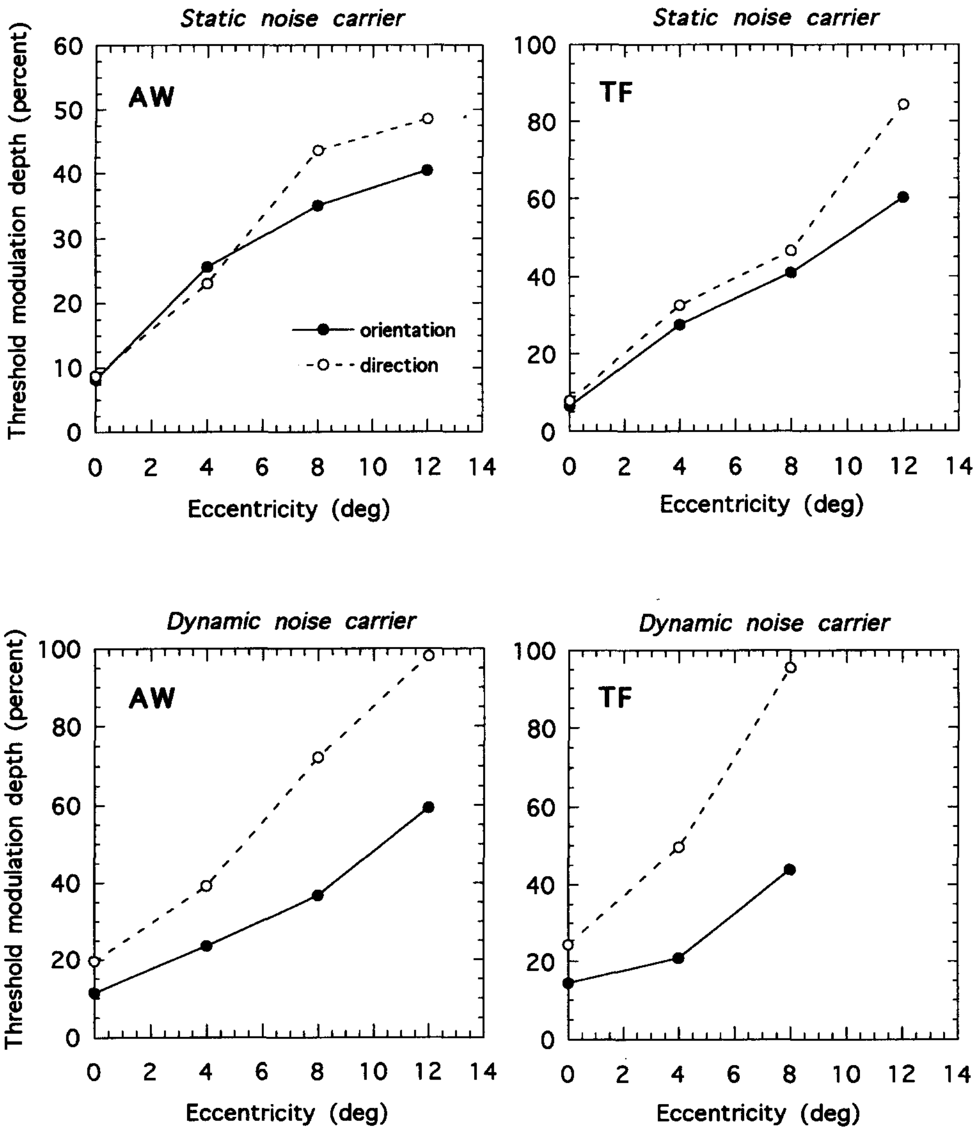

FIGURE 5. Thresholds for detecting the orientation and the direction of a drifting contrast modulation, as a function of stimulus eccentricity. The spatial frequency of the contrast envelope was 1 c/deg. The carrier was either static 2-D noise (upper panels) or dynamic 2-D noise (lower panels). Results for two subjects are shown separately.

is much lower than first-order sensitivity in the fovea, so an equal rate of decline will cause sensitivity to reach zero at a lower eccentricity in the case of second-order motion. Figure 6 shows the direction thresholds obtained in Experiment 2, normalized to take account of different foveal sensitivities for the two types of motion. This reveals the rate of decline of sensitivity independently of differences in absolute sensitivity. The rate of decline is very similar for the two types of motion.

CONCLUSIONS

The results of Experiment 1 show that sensitivity to drift speed is quite different for first- and second-order motion. For first-order motion, the sensitivity function peaks at medium drift temporal frequencies (around 8 Hz), as previously shown in numerous studies (e.g. Watanabe, Mori, Nagata, & Hiwatashi, 1968; Kelly, 1979). For second-order motion, the function is low-pass, peaking at very slow speeds and declining rapidly as speed increases. A previous study (Lu & Sperling, 1995), suggesting that the two temporal sensitivity functions are similar, used a static noise carrier. In that study it is likely that detection was based on local first-order motion components, giving identical results to those obtained with standard first-order motion patterns. This interpretation is suggested by the fact that orientation and direction thresholds were the same when the experiment of Lu and Sperling (who measured only direction thresholds) was repeated in the present study; this occurs only for first-order motion (Smith & Ledgeway, 1997).

The results of Experiment 2 show that sensitivity declines with eccentricity at a similar rate for first- and second-order motion. In our previous study (Smith *et al.*, 1994) which reached the same conclusion, it is likely that the use of static noise carriers led to the presence of local first-order components that were more visible than the second-order motion itself. Again, this interpretation is

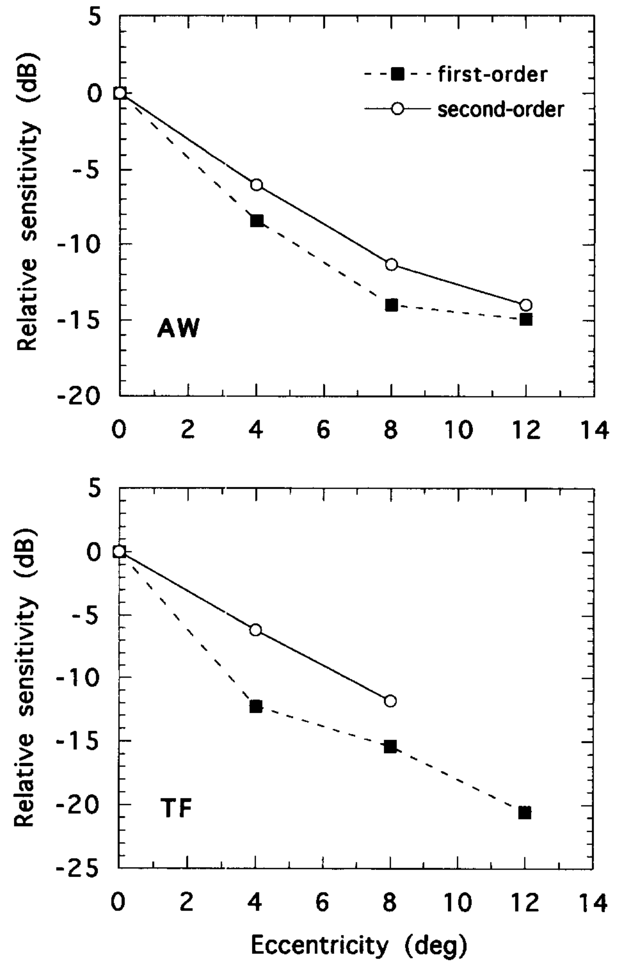

FIGURE 6. The direction thresholds illustrated in Fig. 5 expressed in terms of relative sensitivity to allow comparison of results obtained using contrast modulation of static noise (presumed to be detected by the first-order motion system) and of dynamic noise (second-order motion system). Normalized sensitivity functions, calculated from the thresholds in the same way as for Fig. 4, are shown separately for the two subjects.

suggested by the fact that orientation and direction thresholds were the same in the experiment of Smith *et al.* (1994). However, as it happens, the conclusion is the same when an image that successfully isolates the second-order motion mechanism is used.

Thus, the second-order motion system, although it has many properties in common with the first-order motion system, has at least two features that distinguish it. Firstly, it is not capable of signalling direction at the threshold for detecting orientation. Secondly, its temporal resolution is markedly worse than that of the first-order system.

Note added in proof—We have recently eliminated the possibility that the reduced temporal acuity shown in Fig. 4 results from selective masking of high temporal frequencies by the dynamic noise carrier. We find very similar functions when high-pass spatial-frequency-filtered static noise is used in place of dynamic noise.

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