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Speed Discrimination Thresholds for First- and Second-order Bars and Edges

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Speed discrimination thresholds were measured for first- and second-order Gaussian bars and edges as a function of speed and the spatial scale of the modulation signal. Discrimination thresholds were generally higher for the second-order patterns when compared with modulations of luminance. There were no systematic effects of variations in the width of the bars and edges. The results are discussed in relation to mechanisms for the explicit recovery of contrast modulations and the influence of the form of the carrier signal on visual performance in second-order motion tasks. © 1997 Published by Elsevier Science Ltd.

Second-order   Non-Fourier   Motion   Velocity discrimination

INTRODUCTION

The Fourier transform of a rigidly moving luminance-defined object has all its energy on a line (or plane) through the frequency space origin. The slope of the line is a measure of the speed of motion. However, there is a class of non-rigid motion stimuli which do not have this property. Such stimuli have been described as "second-order" (Cavanagh & Mather, 1989) or "non-Fourier" (Chubb & Sperling, 1988). These often involve the modulation of first-order characteristics of a carrier (i.e., amplitude and frequency). The velocity of the modulation is given by the local orientation of the energy in the Fourier transform but this locally oriented energy is not aligned with the frequency domain origin (Fleet & Langley, 1994).

Given the prevalence of amplitude modulation (AM) and frequency modulation (FM) in communications technology, it is not surprising that ideas from communications theory on the recovery of modulations in AM and FM signals have been applied to the recovery of second-order motion (Sperling, 1989). These techniques aim to extract the modulation, using a mixture of linear filtering and nonlinear processing, whilst discarding the carrier. Models of human motion perception which propose an explicit mechanism for the encoding of second-order motion (Chubb & Sperling, 1988; Werkhoven *et al.*, 1993; Wilson *et al.*, 1992) include at least two motion channels, a Fourier channel and an additional non-Fourier channel, which includes demodulation prior to analysis using motion energy techniques (Adelson & Bergen, 1985; Heeger, 1987; van Santen & Sperling, 1985).

Amongst proponents of "two channel" models, there have been a number of proposals about the form that the initial filtering and nonlinearity may take in the extraction of second-order motion. Chubb & Sperling (1988, 1989, 1991) proposed an initial stage of filtering with a "best of both worlds" filter that is constructed by adding a low-pass temporal filter to another filter which approximates a temporal differentiator. Since the input to the visual system contains only positive values some form of band-limited filter has to be applied for a rectification or squaring nonlinearity to have any radical effect on the input signal. Wilson *et al.* (1992) proposed an initial preprocessing stage involving oriented spatial filters followed by a squaring nonlinearity. Motion energy is calculated in the second-order channel with a filter tuned to a lower spatial frequency and a different orientation to that used in the prefiltering stage. The primary motivation for this stage is the detection of the motion of texture boundaries. A similar two-stage model incorporating fine scale filters, rectification and subsequent coarse scale filtering has been suggested as part of the neural mechanisms underlying the properties of cortical cells which respond to contrast envelopes (Zhou & Baker, 1993, 1994). Werkhoven *et al.* (1993) developed a multistage model which includes band-pass filtering at the retinal level to deliver a signal related to stimulus contrast. The contrast signal is then passed through a single low-pass spatial filter prior to full-wave rectification and motion energy extraction. Others have supported additions to this architecture. Solomon & Sperling (1994) include a half-wave rectification channel. McGowan & Chubb (1994) proposed an additional non-Fourier mechanism with a broadly tuned spatial prefilter most sensitive at high temporal frequencies. Smith (1994) and

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Lu & Sperling (1995) include a feature extraction process in addition to the usual first-order and second-order channels. Further debate surrounds the locus and mechanisms involved in the integration of the information encoded in separate channels.

There is, however, some evidence which would argue against the idea of a special mechanism for the extraction of contrast modulations. Johnston & Clifford (1995a) showed that perceived speed of contrast modulations of sine wave gratings depended upon the spatial frequency and speed of the carrier. For carriers of moderate spatial frequency moving at the same speed but in the opposite direction to the modulation signal, the modulation appeared stationary. Full-wave rectification has the effect of introducing oriented energy through the origin in the Fourier transform whatever the characteristics of the carrier signal and therefore one would not naturally predict an effect of changing the carrier on the basis of the motion from Fourier components approach. However, the results are readily predicted by a local spatio-temporal gradient model (Johnston & Clifford, 1995a). In a companion paper (Johnston & Clifford, 1995b) we showed that reversals of perceived direction of motion with changes in viewing distance, which have been taken as evidence for separate first- and second-order motion channels (Chubb & Sperling, 1989), were predicted by the gradient model without any change of parameters. We also showed that changes in perceived direction induced by grey inter-frame intervals in sampled motion displays (Georgeson & Harris, 1990; Pantle & Turano, 1992), which were considered to indicate the operation of a feature-tracking or correspondence based motion system, could also be predicted by a motion from the multiple spatio-temporal gradient scheme.

The experiments to be described here compare the performance of the visual system in a speed discrimination task for first- and second-order motion patterns. Typically first-order patterns, viewed foveally, give rise to speed discrimination thresholds (SDTs) which vary between 0.04 and 0.1 over a range of velocities from 2 to 64 deg/sec (all SDTs will henceforth be given as Weber fractions). SDTs plotted against velocity follow a characteristic U-shaped relationship. Similar results have been found for random dot patterns (De Bruyn & Orban, 1988) and luminance bars (Orban *et al.*, 1984; Orban *et al.*, 1985) over a wide range of target velocities. With increasing eccentricity the lower end of the U-shaped function is shifted towards higher velocities and the velocity at which optimum SDTs occur is increased. However, the upper limit appears to remain constant (De Bruyn & Orban, 1988). A number of studies have measured velocity discrimination in sine wave gratings (McKee *et al.*, 1986; Muller & Greenlee, 1994; Panish, 1988; Smith, 1987; Smith & Edgar, 1991; Thompson, 1983) and Panish (1988) additionally examined SDTs in Gaussian luminance bars. Although the velocity ranges used by these studies are smaller than those used by Orban *et al.*, results for gratings and Gaussian bars are similar to those for luminance bars and random dots.

McKee *et al.* (1986) showed that SDTs appear to be insensitive to fluctuations in contrast over a wide range of suprathreshold stimulus contrasts. They also showed SDTs are resistant to random variation in spatial frequency although Smith (1987) found raised thresholds above 8–10 deg/sec when spatial frequency was varied randomly around 1 c/ deg. Watamaniuk *et al.* (1993) found that motion discrimination thresholds measured using random-dot kinematograms remained constant even when the motion sequence included abrupt changes in dot density, a manipulation that appeared to change perceived speed. Orban *et al.* (1984), measuring velocity discrimination in bars of differing lengths, found little difference in SDTs for bars of length 7 deg and bars of length 1 deg. De Bruyn & Orban (1988) studied the effect of stimulus duration over a larger range of velocities (1 to 256 deg/sec) and concluded that, for all velocities tested, optimal SDTs are reached with stimulus durations above 200 msec. Also Snowden & Braddick (1991) examined the effect of stimulus duration on SDTs in random dot patterns and found thresholds increased for very brief presentations (below 120 msec). It would seem reasonable to conclude that for first-order stimuli, presented at low to moderate speeds, with stimulus durations beyond 120 msec, speed discrimination is fairly robust to changes in spatial parameters of the stimulus and is determined primarily by stimulus velocity.

Turano & Pantle (1989) measured speed discrimination thresholds for both sine wave contrast modulations of static sinusoidal carriers and sine wave luminance gratings. They showed that there was little difference in SDTs between the two types of stimulus at contrasts and modulation depths 5–10 times above their respective detection thresholds. SDTs for the contrast-modulated gratings appear to be slightly higher, although this effect is more pronounced at low velocities (0.75 and 1.5 deg/sec) and may disappear altogether in the intermediate velocity range (3, 6 and 12 deg/sec). There seems to be no real difference between the two stimulus types in terms of the shape of velocity discrimination curves and Turano and Pantle state that "velocity discrimination with the two types of stimuli appears equivalent" (Turano & Pantle, 1989, p. 218). Cropper (1994) provides additional support for this view. Cropper found that speed discrimination thresholds for gratings and luminance beats, generated by the addition of gratings of slightly different spatial frequencies moving in opposite directions, were similar if the contrasts were matched in terms of multiples of detection threshold contrast. Turano and Pantle conclude that their results support Henning and colleagues' (Henning *et al.*, 1975) hypothesis which proposes that processing elements are arranged to be sensitive to both low frequency luminance modulations and to low frequency contrast modulations of a high frequency carrier.

The question arises whether this similarity in the magnitudes of first- and second-order speed discrimination thresholds generalises to other carrier signals. There is some evidence that the form of the carrier can influence

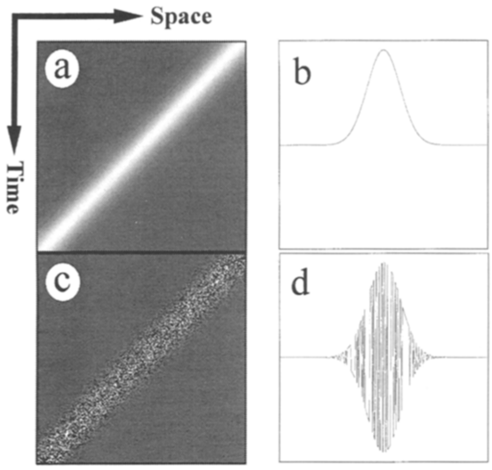

FIGURE 1. (a) A space–time plot of an example of a first-order Gaussian bar. (b) A section of the space–time image showing the spatial luminance profile of the stimulus in A. (c) A space–time plot of a second-order bar and (d) its luminance profile. For purposes of illustration the second-order bar is not drawn to scale. Typically the bars are much narrower in relation to the dynamic noise carrier than is shown here.

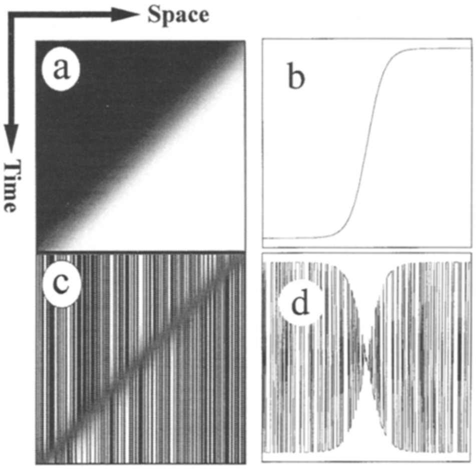

FIGURE 2. (a) A space–time plot of an example of a first-order Gaussian edge. (b) A section of the space–time image showing the spatial luminance profile of the stimulus in (a). (c) A space–time plot of a second-order edge and (d) its luminance profile. For purposes of illustration the second-order edge is not drawn to scale. Typically the edges are much narrower in relation to the noise carrier than is shown here.

the perception of the motion of contrast envelopes. Ledgeway & Smith (1994) found that the perceived speeds of contrast modulations of two-dimensional (2D) random block binary carriers and equivalent luminance modulations were very similar, whereas Johnston & Clifford (1995a) found contrast modulations of sine wave carriers appeared to move more slowly than luminance gratings. Any dependency on the nature of the carrier is of interest because an ideal second-order mechanism should be insensitive to the characteristics of the carrier. On inspection, the motion of beats and amplitude modulations of sine wave gratings appear relatively smooth but this is not true of all second-order stimuli. One typically sees fluctuations in both the apparent speed and the direction of motion of the envelope in modulations of dynamic noise and in modulations involving phase reversals. These fluctuations would be expected to raise velocity discrimination thresholds. In addition, a dynamic noise carrier gives rise to a velocity field with a wide distribution of speeds and directions of motion. It is quite possible that it may be more difficult to detect a difference in the speed of a contrast envelope in the presence of this kind of motion noise. To investigate the role of the carrier in second-order motion we compared speed discrimination thresholds for first- and second-order stimuli as a function of stimulus width and speed using one-dimensional (1D) binary noise carriers.

METHOD

Descriptions of stimuli

First-order bars. This stimulus consisted of a smoothly translating Gaussian bar. A space–time image of the stimulus is shown in Fig. 1(a) and a spatial cross-section of the luminance profile is shown in Fig. 1(b). In all cases other than the Gaussian bar the display mean luminance was 15.5 cd/m^2. The Gaussian bar is defined as a deviation from this baseline level. Display minimum luminance was 1.0 cd/m^2 and maximum luminance of the display was set to 30.0 cd/m^2. The contrast of the first-order Gaussian bar stimulus was 0.32.

Second-order bars. A spatial Gaussian was used to modulate the contrast of binary 1D dynamic noise. A space–time image and a luminance profile of this stimulus are shown in Fig. 1(c) and Fig. 1(d), respectively. The stimuli were scaled to fill the available luminance range. The maximum contrast of the second-order bars and first- and second-order edges was 0.94. For all second-order stimuli the modulation depth was 1.0.

First-order edges. This stimulus consisted of a smoothly translating edge. Luminance varied between 1.0 and 30.0 cd/m^2. A space–time image and luminance profile of this stimulus are shown in Fig. 2(a) and Fig. 2(b). The profile of the edge closely approximates the integral of a Gaussian.

Second-order edges. A smoothly moving edge was used to modulate the contrast of static 1D noise. Figure

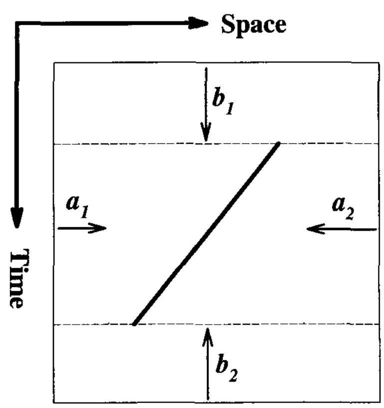

FIGURE 3. Moving bars and edges were clipped by spatio-temporal windows which in varied in extent and duration around set mean values. See Table 1 for parameter values used in the experiments.

TABLE 1. The values that can be taken by the parameters shown in Fig. 3

	Experiment	
	1 and 2	3 and 4
Spatial clipping (dva)	0.0→0.54	none
Temporal clipping (frames)	0→32	11→21
Number of frames	128	64

For example, in Experiments 1 and 2, a_1 and a_2 can take values between 0.0 and 0.54 degree of visual angle (dva). Parameters b_1 and b_2 can take values between 0 and 32 frames.

2(c) and Fig. 2(d) show a space–time image and luminance profile of this stimulus. The modulation, which has the same profile as the first-order edge, is defined such that its magnitude varies from a minimum of −1.0 to a maximum of +1.0. The negative values on one side of the edge have the effect of reversing the polarity of the contrast. The contrast is set to the absolute value of the modulation function.

Spatio-temporal clipping

A potential problem in speed discrimination tasks is that judgements may be based upon factors other than apparent speed (McKee & Watamaniuk, 1994). McKee & Watamaniuk (1994) identify four factors that may covary with velocity; stimulus duration, distance covered, perceived contrast and temporal frequency. Differences in duration and temporal frequency are less discriminable than differences in velocity (Orban *et al.*, 1984; McKee *et al.*, 1986). Therefore, at least at mid-range speeds where optimum discrimination is obtained, SDTs should be based on velocity information rather than duration or temporal frequency. Although Weber fractions for distance discriminations are generally lower than those for speed discriminations (Burbeck, 1987) one can ensure subjects rely on the velocity cue by randomly varying the distance travelled by the stimulus.

In the present study a number of random factors have been included in the design of the stimuli to reduce the reliance on cues other than the speed of motion. In order to ensure subjects did not utilise the duration of the stimulus as a cue to speed we randomly varied the time of onset and stimulus duration within certain limits. In order to ensure subjects did not utilise the distance travelled as a cue to speed the stimulus was displayed within a spatial window which varied in position and extent, within certain limits, on each trial. On any trial these variables, the spatial and temporal clipping parameters (see Fig. 3 and Table 1), interact to determine both the temporal duration and distance travelled. Relatively slow moving stimuli will primarily be affected by temporal clipping and relatively fast moving stimuli by spatial clipping. For the first- and second-order bars the display was set to the mean luminance whenever the stimulus fell outside the space–time region bounded by lines a_1, a_2, b_1, b_2. When a bar stimulus appeared it was always moving. In the case of the first- and second-order edges the edge remained on the screen for the entire duration of the trial. For some of that time it could be stationary—clipping determined the start or end positions of the movement of the edge. Once the clipped area had been determined the bar or edge was positioned so that it always went through the centre of the space–time region. Table 1 shows the limits within which the random values could range for each of the five experiments. The "jitter" could vary the spatial displacements and temporal intervals by up to approximately $\pm 33\%$ of their mean values. In addition, two different samples of motion are presented simultaneously on each trial which agree in their speed but differ in their temporal duration and spatial displacement. Thus, it is very unlikely that subjects would gain an advantage from using spatial displacement or temporal duration as cues in place of apparent speed. The polarity of the first-order edge was randomly reversed across trials.

Procedure

Thresholds were measured using the Method of Single Stimulus (Westheimer, 1977) combined with an Adaptive Method of Constants procedure (Watt & Andrews, 1981). In our task, subjects have to decide whether a target stimulus is going faster or slower than an internal reference corresponding to a particular stimulus velocity. Feedback is given on all test trials. Feedback is given to aid the maintenance of an internal standard against which the speed of motion of each stimulus is compared. For trials on which the test and standard have the same value the feedback signal is chosen at random. Trials for first- and second-order stimuli were interleaved. Each psychometric function was based on the responses from a single run consisting of 64 trials.

Each run consisted of three stages; presentation of standard stimuli, training on a small training set with feedback to establish an internal standard, and finally, testing on the main stimulus set. To take a concrete example, subjects are first presented with the "standard" stimuli e.g. first- and second-order bars moving at 2 deg/sec. These stimuli provide the standard against which all others in the batch should be judged. Subjects are shown two of each of these randomly shuffled together. No response is required. Subjects are then presented with a training set which contains 10 first- and 10 second-order stimuli that are moving either faster or slower than the standard stimuli. The subject has to indicate by pressing one of two keys whether he thinks the stimulus is moving faster or slower than the standard. Data collection follows directly after the training period. Subjects are given the facility to repeat a stimulus on lapses of attention, but as the stimuli are freshly generated on each presentation, the stimulus will be drawn at random from the trials remaining. The adaptive procedure is constrained such that the mean of the velocities of the test stimuli is equal to the velocity of the standard stimuli.

The data obtained were subject to standard probit analysis (Finney, 1971). The standard deviation of the subject's responses in degrees per second represents the increment in velocity that would be needed for that

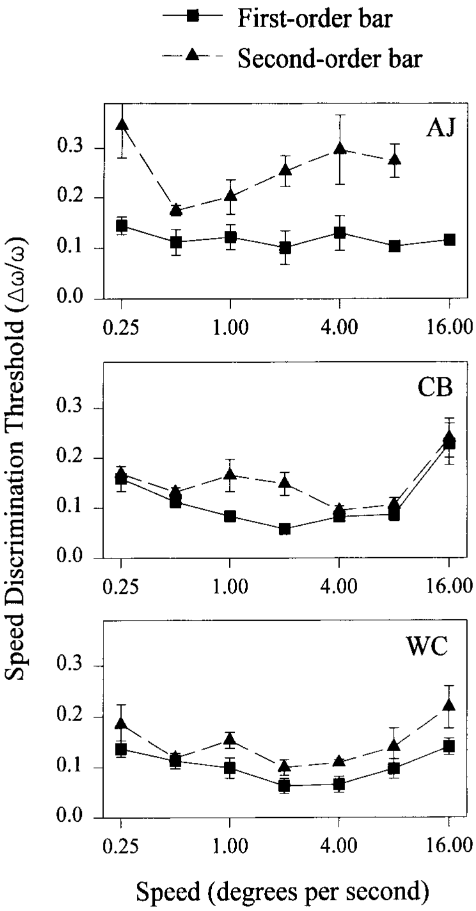

FIGURE 4. Weber fractions describing speed discrimination for first- and second-order bars as a function of the standard speed. Data are shown for three subjects. The bars indicate ± 1 SE.

subject to judge the test stimulus as moving faster than the standard stimulus 84% of the time. The usual criteria for velocity discrimination is 75%, a point that occurs 0.674 standard deviations from the mean on the normal distribution curve. Thus, the standard deviation was multiplied by 0.674 before being divided by the velocity of the standard stimulus to deliver the Speed Discrimination Threshold (SDT) as a Weber fraction. All thresholds are expressed as Weber fractions unless otherwise specified. For each stimulus level, for each subject, a minimum of three such measures were obtained.

All subjects were expert psychophysical observers with normal or corrected vision. Stimuli were viewed binocularly in a darkened room from a distance of 2 m. Two slightly different forms of the same stimulus were presented simultaneously to the left and right of a fixation spot to aid fixation and reduce any tendency to track the stimulus. Both of these images had the same stimulus speed, bar/edge width and type but they were generated with different random values for spatial clipping, and temporal clipping. One of the stimuli moved upwards whilst the other moved downwards. The side of the display containing upward motion was randomised from trial to trial. Subjects were instructed to maintain fixation on the fixation spot during stimulus presentation.

Equipment and display

Gamma corrected space–time images were constructed in PC RAM and passed to a Matrox Image-1280 graphics card. The Gamma correction was determined by carefully measuring screen luminance using a UDT spot photometer. Data were loaded, frame by frame, from the space–time image into an output look-up table indexed by a ramp drawn in display memory. Each horizontal line in the space–time image (see Figs 1 and 2) represents one frame which is effectively constructed by spatially repeating that line across a region of the display device. The graphics card delivered 8 bits per pixel to give 256 grey levels. Images were displayed on a Manitron monochrome monitor equipped with a P31 phosphor. Slightly different versions of the same stimulus were presented simultaneously in two vertically aligned windows to the left and right of a fixation spot. The distance between the fixation spot and the centre of each window was 1.42 deg of visual angle. The windows themselves were square, each side measured 2.10 deg. Each pixel subtended 0.49 arc min. In Experiments 1 and 2 stimuli were 128 frames long whilst in Experiments 3–5 the stimuli were 64 frames long. The frame rate was 59.5 Hz. There was a minimum of a 1 sec gap between stimulus presentations. On each trial the screen around the stimulus was set to display mean luminance and the full screen reverted to display mean luminance between trials.

RESULTS

Experiment 1: speed discrimination in first- and second-order bars as a function of velocity

Weber fractions for speed discrimination were measured as a function of velocity for first- and second-order bars. Three subjects were tested at seven standard speeds; 0.25, 0.5, 1.0, 2.0, 4.0, 8.0 and 16.0 deg/sec. For both the first- and second-order bars and over all stimulus levels, the standard deviation of the Gaussian was set to 0.9 arc min. Speed discrimination thresholds are shown in Fig. 4. The data for each of the observers were subject to analysis of variance. SDTs for second-order bars are significantly higher than those for first-order bars for each of the subjects tested (AJ, $F_{1,40} = 7.80$, $P < 0.01$; CB, $F_{1,45} = 9.53$, $P < 0.01$; WC, $F_{1,44} = 14.08$, $P < 0.01$).

For two of the subjects (CB and WC) the SDTs follow a U-shaped pattern with thresholds for first-order stimuli dropping to about 0.06 for a base velocity of 2.0 deg/sec. Data for the third subject are relatively invariant with velocity (AJ, $F_{6,40} = 1.55$, n.s.). Whilst raised SDTs at low base velocities are a common finding (McKee, 1981; McKee *et al.*, 1986; Panish, 1988), Orban *et al.* (1985) found no upturn in the speed discrimination function until speeds reach around 64 deg/sec. In the present study the stimulus, when travelling at 16 deg/sec, traverses a maximum distance of 2.1 deg and a minimum distance of 1.0 deg (depending upon random spatial jitter). The stimulus will, therefore, only be moving for a period of between 60 and 130 msec. It seems reasonable to assume

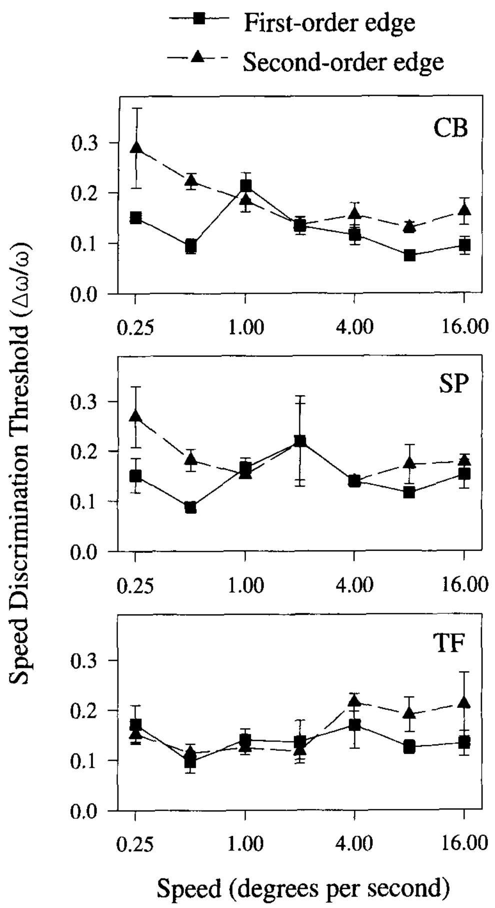

FIGURE 5. Weber fractions describing speed discrimination for first- and second-order edges as a function of the standard speed. Data are shown for three subjects. The bars indicate ±1 SE.

that the higher SDTs found at 16 deg/sec are due to the brief amount of time that subjects have to extract velocity information from the stimulus (Snowden & Braddick, 1991). In the present study the stimuli were vertically moving bars of length 2.1 deg centred 1.4 deg right and left of the fixation spot. The fact that Orban *et al.* (1985) found little effect on the upper end of the SDT curve with increasing eccentricity would suggest that the presentation of stimuli in the near periphery would have little influence at the highest speed used here. Analysis of the data in Fig. 4 shows that whilst the SDTs are generally higher for the second-order stimuli there are no significant interactions between stimulus type and speed for any of the subjects investigated, hence there is no evidence that the shapes of the velocity tuning curves differ for first- and second-order motion.

Experiment 2: speed discrimination in first- and second-order edges as a function of velocity.

Figure 5 shows Weber fractions for speed discrimination as a function of speed for first- and second-order edges. Three subjects were tested on seven base velocities; 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, and 16.0 deg/sec. For both the first- and second-order edges over all stimulus levels, the edge width, defined as the space constant of the Gaussian integral, was set to 1.25 arc min. The noise had a pixel width of 0.49 arc min. The Gaussian bars appeared as translating noisy disturbances. In the case of the second-order edge the carrier is static rather than dynamic but the polarity inversion induces transient reversals of motion described by Anstis & Rogers (1975) as reversed phi. Where there is a difference between first- and second-order edge discrimination thresholds, the thresholds for the second-order edges are higher. Thresholds for first- and second-order edges, averaged over speed, were significantly higher for CB ($F_{1,35} = 16.73$, $P < 0.01$), marginally higher for SP ($F_{1,31} = 3.87$, $P = 0.058$) and not significantly different for TF ($F_{1,65} = 0.73$, n.s.). For all observers there appears to be no difference between the SDTs for the two types of stimuli for mid-range speeds (1, 2, 4 deg/sec).

Experiment 3: effects of contrast and modulation depth

Previous studies have shown velocity discrimination thresholds for first- and second-order motion patterns were similar for stimuli presented at equal multiples of the detection threshold contrast (Turano & Pantle, 1989; Cropper, 1994). Our strategy was to investigate optimal performance and thus all stimuli were presented at maximum contrast. In the case of Gaussian bars the maximum contrast was 0.32. For the second-order bars the modulation depth was 1.0 (maximum contrast was 0.94, minimum contrast was zero). McKee *et al.* (1986) showed that velocity discrimination in sinusoidal gratings was independent of contrast (when contrast was varied from 0.05 to 0.82) and Turano & Pantle (1989) found that contrast needed to be reduced to about 0.05 for a significant reduction in performance in speed discrimination. In order to establish that the values for contrast and

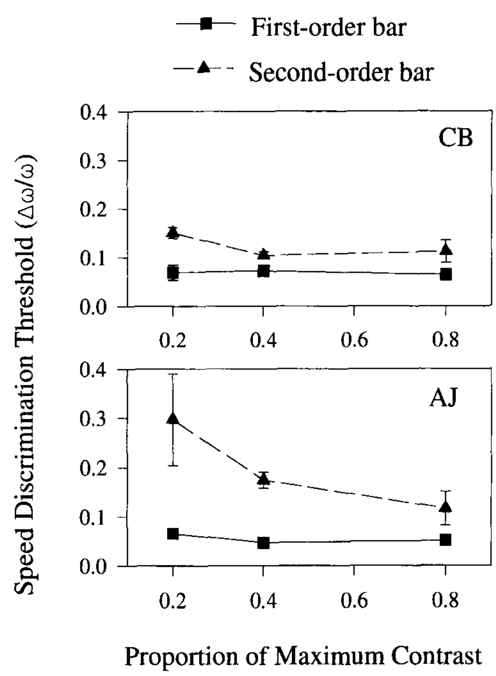

FIGURE 6. Weber fractions describing speed discrimination for first- and second-order bars as a function of contrast. The abscissa quantifies contrast as a fraction of maximum contrast for each stimulus. The Gaussian bar has a maximum contrast of 0.32, whereas the Gaussian edge has a maximum contrast of 0.94. Data for two subjects are shown. The bars indicate ±1 SE.

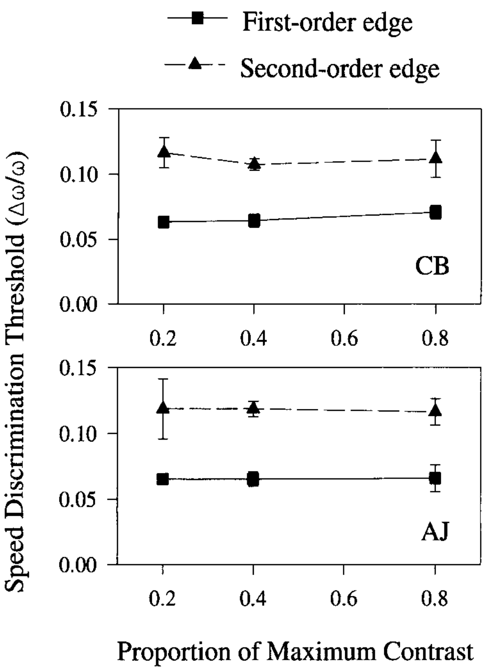

FIGURE 7. Weber fractions describing speed discrimination for first- and second-order edges as a function of contrast. The abscissa quantifies contrast as a fraction of maximum contrast for each stimulus. The maximum contrast of first- and second-order edges was 0.94. Data for two subjects are shown. The bars indicate ± 1 SE.

modulation depth used in the present study are well above the levels at which the response of processes governing the perception of velocity have reached saturation with respect to these parameters, we measured speed discrimination thresholds for a range of stimulus contrasts. The standard velocity was set to 2 deg/sec. The spatial parameters were the same as in the first two experiments. Data for three levels of contrast and two subjects are shown for bars in Fig. 6 and edges in Fig. 7. In each case, contrast is expressed as a percentage of the maximum contrast. There is no significant effect of contrast for first- and second-order edges for either subject over the range tested. Thresholds appear to be raised in the case of second-order bars at low contrasts but again analysis of variance showed no significant effects of contrast. In this experiment Weber fractions were higher for both second-order motion stimuli (bars: CB, $F_{1,14} = 22.32$, $P < 0.01$; AJ, $F_{1,12} = 17.69$, $P < 0.01$; edges: CB, $F_{1,17} = 33.13$, $P < 0.01$; AJ, $F_{1,15} = 13.13$, $P < 0.01$).

Experiment 4: speed discrimination in first- and second-order bars as a function of bar width

In Wilson's model (Wilson *et al.*, 1992; Wilson & Kim, 1994) postrectification filters are tuned to spatial frequencies one octave lower than the prefilters. In general, one would expect mechanisms designed to recover contrast modulations to be tuned to lower spatial frequencies than prefilters designed to respond to a carrier signal. In order to investigate any dependencies on scale we measured thresholds at a range of bar widths. Two subjects were tested on five bar widths with the standard deviations for the Gaussian set to the following: 0.45, 0.9, 1.8, 3.6, 7.2 arc min. The noise had a pixel width of 0.49 arc min and the standard speed was set to 2.0 deg/sec. The data are presented in Fig. 8. The SDTs for the second-order bars are higher than those for the first-order stimuli (CB, $F_{1,22} = 15.04$, $P < 0.01$; WC, $F_{1,22} = 13.92$, $P < 0.01$). For both types of stimuli, analysis of variance showed no significant effect of bar width on SDTs. Thresholds were around 0.055 for the first-order bars and around 0.09 for the second-order bars.

Experiment 5: speed discrimination in first- and second-order edges as a function of edge width

Two subjects were tested on five edge widths with the space constant of the Gaussian integral set to the following values: 1.25, 2.5, 5, 10, 20 arc min. The standard velocity was set at 2.0 deg/sec. Figure 9 shows Weber fractions for speed discrimination thresholds as a function of edge width. Where there is a difference, SDTs appear to be slightly higher for the second-order stimuli. However, there only appear to be differences at the endpoints of the stimulus range. Analysis of variance found no main effect of stimulus type (CB, $F_{1,23} = 3.61$, $P = 0.07$; WC, $F_{1,22} = 3.7$, $P = 0.067$). With edges of width 10 arc min both subjects perform equally well on both the first- and second-order edges. Compared with the data from Experiment 2, it can be seen that the SDTs found in this experiment are lower. Furthermore, for both subjects in the present experiment, SDTs were lower for first-order edges than for second-order edges at a stimulus width of 1.25 arc min (the width used in Experiment 2), as was also the case in Experiment 3.

Summary

Speed discrimination was investigated for first- and second-order Gaussian bars and edges as a function of stimulus speed and width. Second-order stimuli were

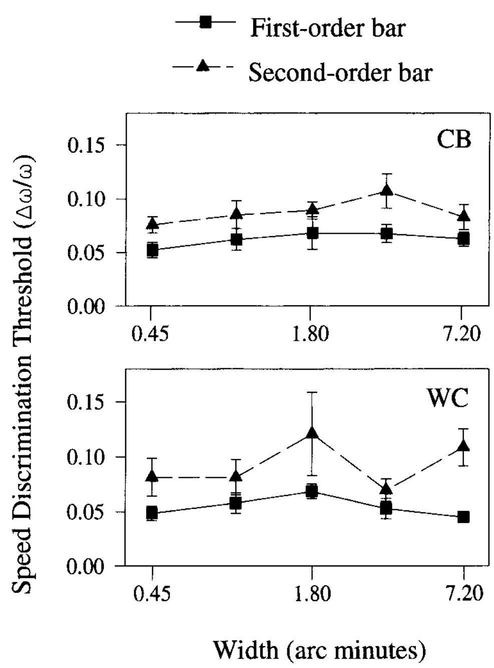

FIGURE 8. Weber fractions describing speed discrimination for first- and second-order bars as a function of bar width. Data are shown for two subjects. The bars indicate ± 1 SE.

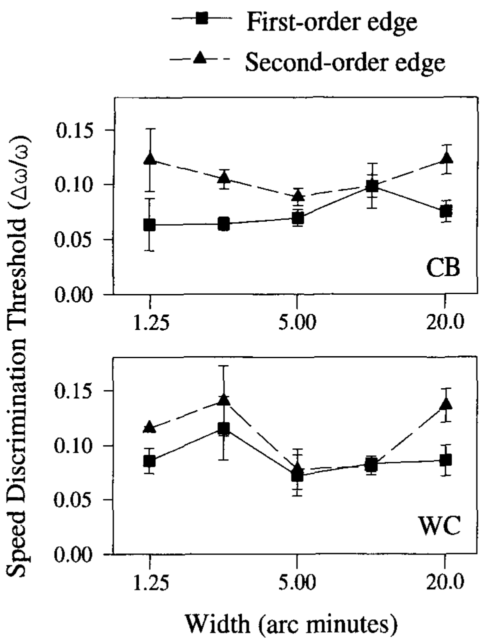

FIGURE 9. Weber fractions describing speed discrimination for first- and second-order edges as a function of edge width. Data are shown for three subjects. The bars indicate ±1 SE.

contrast modulations of binary random noise. The second-order bars involved modulations of 1D dynamic noise. For the second-order edges we modulated the contrast of 1D static noise. Discrimination thresholds for second-order bars were higher that those for first-order bars but there was no evidence for any systematic differences between first- and second-order stimuli in the shape of the functions relating discrimination thresholds to speed or bar width. For edges the data are less clear. Where there is a difference one finds that thresholds are higher for the second-order stimulus than for the first-order stimulus. However, speed discrimination performance does not differ greatly for mid-range speeds and edge widths.

DISCUSSION

Typically, differences in perception or task performance in first- and second-order motion tasks are explained with reference to the architecture of the motion analysis system. The generic approach to the recovery of the motion of a contrast envelope involves band-limiting the luminance signal using linear spatio-temporal filters in order to produce a signal with positive and negative values, and then rectifying or squaring the resulting signal prior to motion analysis. In this view, an additional Fourier channel is included to account for phenomena such as the reversed phi effect which depend upon changes in the sign of stimulus contrast (Chubb & Sperling, 1989). However, differences in discrimination performance that depend upon the nature of the carrier signal are not readily explained in terms of architecture. The increase in discrimination thresholds for dynamic 1D noise carriers with respect to first-order modulations of luminance cannot be attributed to some intrinsic property of a second-order motion channel because one does not find an equivalent loss of performance with sine wave carriers (Turano & Pantle, 1989; Cropper, 1994). A pointwise ideal rectification or squaring operation would allow the recovery of the envelope, whatever the carrier signal. Thus rectification, in itself, cannot explain the effects found here. Similarly, any explanation based on the nature of postrectification processing would need to be based on the quality of the signal reaching motion analysis mechanisms which would be determined by the stimulus properties, any early nonlinearity and the prerectification spatio-temporal filters.

In second-order patterns, peaks of energy in the power spectrum do not appear at the spatio-temporal locations corresponding to the speed of the modulation. Therefore consideration has been given to the proposal that the perception of second-order motion depends upon the detection of the movement of a distortion product caused by nonlinearities early in visual processing (Burton, 1973), which would be equivalent to adding a signal of the appropriate velocity to the image sequence. This hypothesis was rejected for contrast modulated sine waves by Turano & Pantle (1989) on the basis of calculations of the magnitude of the hypothetical distortion product. The magnitude of the distortion product was too small to explain velocity discrimination in their stimulus. Badcock & Derrington (1989) tested whether the motion of a spatial beat was detected on the basis of a distortion product. They attempted to null the distortion product by adding a sine wave luminance signal which had the same frequency and phase as the distortion product but which was opposite in sign. They found no substantial effect of the addition of a luminance signal on detection of motion of the beat. Ledgeway & Smith (1994) interleaved first- and second-order motion gratings with a quarter cycle displacement between each frame. If second-order motion perception is based upon an early nonlinearity then a distortion product should have been produced in the second-order frames. This would be equivalent to adding a luminance grating to each frame of the second-order display. Although there would be an amplitude difference between the first-order grating and distortion product one might reasonably expect to detect direction of motion in this kind of display, however, there was no consistent percept of movement in any particular direction.

In addition to the experimental evidence, Johnston *et al.* (1992) and Johnston & Clifford (1995a) showed by simulation that an early nonlinearity is not necessary for the detection of motion of contrast modulations of sine wave gratings. Gradient techniques for motion extraction (Johnston & Clifford, 1995b) can recover the direction and perceived speed of contrast modulations in the low contrast regions of contrast-modulated patterns with no distortion of the motion signals in the image sequence and without explicit recovery of the contrast of the carrier. There is sufficient information present in local regions of the image to recover speed and direction of motion. The fact that there is no energy at the velocity of the contrast modulation in the global Fourier transform does not preclude local measurement of velocity. It would seem then that there is no strong justification for supposing that the perception of contrast modulations of sine wave gratings is based on an early nonlinear distortion of the luminance signal.

It is likely that the raised discrimination thresholds in the second-order patterns used here are due to increased noise in the stimulus, which leads to more variable outputs in linear filters early in the motion pathway. This might explain the observation that threshold elevations were more consistently seen for the second-order bars, which had dynamic carriers, than for the second-order edges which were constructed using static carriers. There has been less emphasis on the effects of stimulus noise in studies of second-order motion than on architecture and mechanisms. It is possible that some of the effects which have led to architectural theories may simply reflect the action of stimulus noise on early filters. One way of testing this proposal would be to add dynamic noise to first-order equivalent versions of second-order stimuli to see whether changes in perception of performance occur that are similar to those found when one compares first- and second-order motion patterns (McOwan & Johnston, 1996).

An alternative to the proposal of explicit mechanisms for the recovery of contrast envelope motion is that all motion patterns are processed by a single mechanism which attempts to compute the velocity field for any motion sequence. We have shown previously that spatio-temporal gradient models can detect the motion of some second-order displays (Johnston & Benton, 1996; Johnston & Clifford, 1995b; Johnston *et al.*, 1992). The velocity fields produced in second-order patterns of the kind considered here are likely to contain a wide distribution of velocity values, whereas the velocity fields generated by the first-order patterns are single valued and smooth. If it is assumed discrimination of speed is limited by the variation in the computed velocity field one would predict that thresholds should be higher for the second-order patterns, and the more random variation in the carrier the higher the discrimination threshold.

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