Vision Res. Vol. 23, No. 12, pp. 1533–1538, 1983
Printed in Great Britain.

0042-6989/83 $3.00 + 0.00

DISCRIMINATION OF MOVING GRATINGS AT AND ABOVE DETECTION THRESHOLD*

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(*Received* 29 *November* 1982; *in revised form* 6 *May* 1983)

Abstract—Two experiments examined the discriminability of moving gratings. Experiment 1 measured the difference between detection and discrimination thresholds for gratings of equal spatial frequency drifting in the same direction at different rates. It was found that, as Watson and Robson [*Vision Res.* **21**, 1115–1122 (1981)] had found with counterphase modulated gratings, only very coarse discriminations could be made. The results suggest that just two labelled channels can account for the velocity discrimination of gratings at detection threshold. The second experiment investigated the discriminability of suprathreshold moving gratings. These results also support the idea that rate of movement is mediated by two broadly tuned channels.

INTRODUCTION

Evidence has been mounting over the past few years to suggest that whereas spatial channels are many and narrowly tuned, temporal frequency or movement channels in human vision are few and very broadly tuned. Studies of threshold elevation following flicker adaptation, (Pantle, 1971; Smith, 1971; Nilsson *et al.*, 1975), and perceived rate of movement following movement adaptation, (Thompson, 1980), have lent support to this view. Further convincing evidence has come from Watson and Robson (1981), who investigated the discriminability at detection threshold of counterphase flickering sine-wave gratings which differed either in their spatial frequency or in their rate of temporal modulation. The logic of such detection/discrimination experiments is now well known and has been used to investigate spatial vision by Nachmias and Weber (1975) and Furchner *et al.* (1977). A stimulus at detection threshold is assumed to be detected by a single channel, the most sensitive channel for that stimulus; for two stimuli to be discriminated one from the other at their respective detection thresholds, they must excite different "labelled" detectors. A more rigorous treatment of this argument may be found in Thomas (1982). In one of their conditions Watson and Robson examined the discriminability of gratings of equal spatial frequency but different rates of temporal modulation. At both the spatial frequencies they investigated, gratings of low temporal modulation, (below about 4 c/sec), could be discriminated only from gratings of high temporal frequencies. That is, gratings of low temporal frequencies could not be discriminated from other gratings of low frequencies, nor could high frequencies be discriminated from other high frequencies. This suggests that we might possess only two temporal channels at each spatial frequency.

Watson and Robson used flickering stimuli and their subjects had to discriminate different rates of flicker. It is possible that their stimuli, although they can be decomposed into oppositely moving gratings, are much harder to discriminate than moving gratings would be. The present paper describes, in Experiment 1, a similar procedure to that used by Watson and Robson but using moving rather than counterphase modulated gratings so that subjects could use the perceived velocity of the stimuli in making their discriminations. A second experiment describes the discriminability of moving gratings above their detection thresholds.

METHODS

Computer generated sinewave gratings were displayed on the large screen of a Joyce Electronics display with P4 phosphor. All stimuli appeared as patches in the middle of the screen, being shaped in space with a gaussian window along the X-axis and a raised cosine along the Y-axis. At the contrast levels used in this paper the stimuli appeared as circular patches, approximately 2 deg in diameter. Stimuli were also shaped in time by a gaussian of duration 1.2 sec, above half amplitude for 0.38 sec. Subjects sat 263 cm from the screen which subtended 7×5 deg of visual angle. A bite bar ensured that the subject's head did not move during the experiment and a small spot on the centre of the screen aided fixation. Viewing was binocular. A small LED was positioned close to the subject's right eye and was imaged on the blind spot. Any sizeable eye movement immediately

*These data were first reported to the Association for Research in Vision and Ophthalmology, Sarasota, 1982 (Thompson, 1982b).

rendered this light visible to the subject who took this as a signal to rest before proceeding with observations.*

EXPERIMENT 1: DETECTION/DISCRIMINATION THRESHOLDS OF MOVING GRATINGS

In this experiment all stimuli were vertical sine-wave gratings drifting to the left. A preliminary experiment determined the detection thresholds for each stimulus using a two interval forced choice staircase modelled on that described by Graham *et al.* (1978). The thresholds obtained were used only to select the range of contrasts to be investigated in the main part of the experiment. The discriminability of two patterns which differed only in their rate of movement was then established by presenting 4 contrast levels of each spanning the detection thresholds in a two interval forced choice experiment. The subject had to indicate both the interval which contained the stimulus, the detection task, and the rate of movement of the stimulus, the discrimination task. The discrimination required was simply a choice between "fast" and "slow"; practice trials before the experiments acquainted the subject with the rates of movement to be discriminated. From the data obtained psychometric functions were fitted to both the detection and discrimination data and thresholds for each task obtained.† Most psychometric functions were fitted to a data set comprising 99 presentations of each of the 4 contrast values. On some functions, when the discrimination was either very simple or clearly impossible, only 66 presentations of each contrast value were made.

Two gratings were deemed discriminable at detection threshold when the difference between their detection and discrimination thresholds was less than 1.0 dB. This criterion was chosen as Watson and Robson (1981) have shown that a sensitivity difference of 1 dB or less between detection and discrimination thresholds nearly always indicated a failure to reject the hypothesis that different labelled detectors were responsible for the detection. Pairs of gratings which satisfy this criterion are shown in Table 1. In all the conditions explored several other frequency pairs were investigated, sometimes as many as 6 or 7, never fewer than 2. The table also indicates the pairs investigated which most narrowly failed to be discriminated.

For subject A. H., an experienced observer, unaware of the purpose of the present study, we can see that at 1 c/deg stationary gratings can be just discriminated from 4 c/sec movement at detection threshold; 1 c/sec from 7 c/sec, 2 c/sec from 12 c/sec and 3 c/sec from 17 c/sec. 4 c/sec drifting gratings could not be discriminated from any faster rate, the fastest rate investigated being 24 c/sec. The results from P.T., the author, show slightly better discrimination but the same general trend.

To summarise these results, it appears that provided the slower stimulus is moving at 3 c/sec or below then it can probably be discriminated from some faster rate of movement. Gratings of 4 c/sec cannot be discriminated from any faster rate below 24 c/sec. These results agree closely with those of Watson and Robson. One additional point is noteworthy: as spatial frequency increases so the range of slow movements which can be discriminated from faster rates decreases. That is, at 1 c/deg, 3 c/sec can be discriminated from 16 to 17 c/sec, but at 8 c/deg even 2 c/sec cannot be discriminated from 24 c/sec.

Discussion

These results agree with those of Watson and Robson and suggest that at detection threshold just two labelled temporal channels are required to

Table 1. Just discriminable pairs of moving gratings at detection threshold

Spatial frequency (c/deg)	A.H.	P.T.
1	0–4 (5)	
	1–7 (6)	1–6 (5)
	2–12 (11)	2–7 (6)
	3–17 (16)	3–16 (12)
	4–*	4–*
2	0–5 (4)	
	1–8 (7)	
	2–12 (10)	2–10 (8)
	3–*	3–*
3	1–8 (6)	
	2–10 (9)	
	3–*	
4	0–4 (5)	
	1–7 (6)	1–7 (6)
	2–10 (8)	
	3–*	
6	1–17 (16)	1–9 (8)
		2–16 (12)
	3–*	3–*
8	0–7 (6)	
	1–18 (17)	1–12 (9)
	2–*	2–*
12		1–18 (17)
		2–*

All numbers in the table are temporal frequencies in cycles/second.

Numbers in brackets indicate the temporal frequency investigated which most narrowly failed to be discriminable.

* Refers to a failure to find a discriminable rate of movement below 24 cycles/sec.

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*I am grateful to Simon Heywood for suggesting this simple method for crudely monitoring eyemovements.

† Detection threshold was determined as the contrast at which the stimulus was detected on 82% of presentations. The just discriminable temporal frequency was determined as that frequency which could be discriminated on 82% of trials from the slower moving stimulus. Curves were fitted through the data by a maximum likelihood method described by Watson (1979). I am grateful to Beau Watson for the use of his software.

account for the discrimination of gratings moving up to 24 c/sec. The crossover in sensitivity between the two channels would be around 4 c/sec. If suprathreshold rates of movement were encoded by two channels, a notion suggested by Thompson (1982a) amongst others, then the discriminability of suprathreshold rates of movement might reflect the operation of these channels. Campbell *et al.* (1970), who investigated the "just noticeable discrimination ratio" for stationary sine-wave gratings, wrote: "In the domain of color vision, for example, it is commonly assumed that wavelength discrimination in a particular part of the spectrum reflects the rate of change with wavelength of the response in three color channels." The argument here is that the peaks and troughs of the wavelength discrimination curve reflect the operation of just a few channels, whereas the uniformity of spatial frequency discrimination found by Campbell *et al.* reflects the operation of many channels. It might be noted here that recent work by Yager and Richter (1982) and by Hirsch and Hylton (1982a, b) has shown that the spatial frequency discrimination curve is not smooth but has a scalloped shape.

If rate of movement is coded by just a few channels at each spatial frequency then the determination of the discriminability of moving gratings differing only in their velocity may cast some light on the number and nature of these channels.

EXPERIMENT 2: SUPRATHRESHOLD DISCRIMINATION OF MOVING GRATINGS

Several experiments in the past have measured velocity discrimination by a variety of means. Most of the significant early reports (e.g. Bourdon, 1902; Brown and Mize, 1932), are well reviewed by Brandalise and Gottsdanker (1959) and by Brown (1961). Brown draws a distinction between those papers which measure velocity discrimination with successive stimuli and those with adjacent or superimposed stimuli. Although Weber's law clearly breaks down for velocity discrimination, Brown suggests that the best estimate of $\Delta V/V$ is approximately 0.138 for adjacent stimuli and around 0.0769 for separate stimuli. A recent paper by McKee (1981) has found Weber fractions as low as 0.05 for velocity discrimination of separate stimuli.

All these papers have used stimuli which confound temporal frequency with velocity. Only Pantle (1978) has used sinusoidal grating stimuli, whose spatial and temporal frequency are easily specified. Pantle defined his velocity DL has half the difference between the velocities which gave 25% and 75% discrimination scores. Plotted against temporal frequency his results showed DL minima around 5 c/sec and again at a rate of movement above 15 c/sec. The DL at these minima could be as low as 0.015.

In the present study suprathreashold discrimination of moving gratings was determined as follows. In each experimental session just two stimuli, differing only in their rate of movement, were presented 50 times each, in random order. The subject, familiar with these stimuli from a previous practice session, was required to identify each stimulus as either "fast" or "slow". Over a number of sessions the slower grating was held constant and its discriminability from a range of faster moving gratings determined. This allowed the construction of a "frequency of discrimination curve", from which a just noticeable temporal frequency ratio could be determined, this being defined as the ratio of the just discriminable temporal frequencies, c.f. Campbell *et al.*'s just noticeable spatial frequency ratio in their spatial discrimination experiment.

It is obviously important that the discrimination of the two stimuli could not be made on the basis of contrast differences. Detection thresholds were established for all stimuli and, in the first instance, grating contrasts were set to be a fixed level, either 6.5 or 11.0 dB, above this threshold. For most pairs of stimuli, being close together in their temporal frequency and identical in spatial frequency, this was sufficient to ensure that there were no apparent contrast differences. On those few occasions when there was a discrepancy, the contrast of the faster moving grating was adjusted to match that of the slower stimulus. It should be noted that, for the most part, such adjustment was unnecessary; this suggests that the "contrast constancy" described by Georgeson and Sullivan (1975) for the spatial domain is not as pronounced in the temporal domain.

The results are shown in Figs 1, 2 and 3 for spatial frequencies of 1, 4 and 8 c/deg. The data for the 2 subjects are clearly similar; rates of movement around 4 c/sec are better discriminated than those of lower or higher temporal frequencies. This appears to be the case over the range of spatial frequencies tested. Discrimination at the higher contrast level, 11 dB above threshold is better than that at the lower level, 6.5 dB above threshold. The shape of the discrimination function does not appear to be altered by this change in contrast. It should be noted that the velocity discrimination found here was a good deal worse than that reported by some other authors, (e.g. Pantle, 1978; McKee, 1981). Experiments are currently under way to investigate this discrepancy.

Discussion

These results may be good evidence for the idea that rate of movement is coded by two temporal frequency channels which cross over in their sensitivity around 4 c/sec. This interpretation makes the assumption that at the crossover point of the two channels' sensitivities their relative rate of change would be greatest, and therefore discrimination ratios smallest. However this presupposes that rate of movement is derived from some kind of comparison of the activity in the two channels. This could be

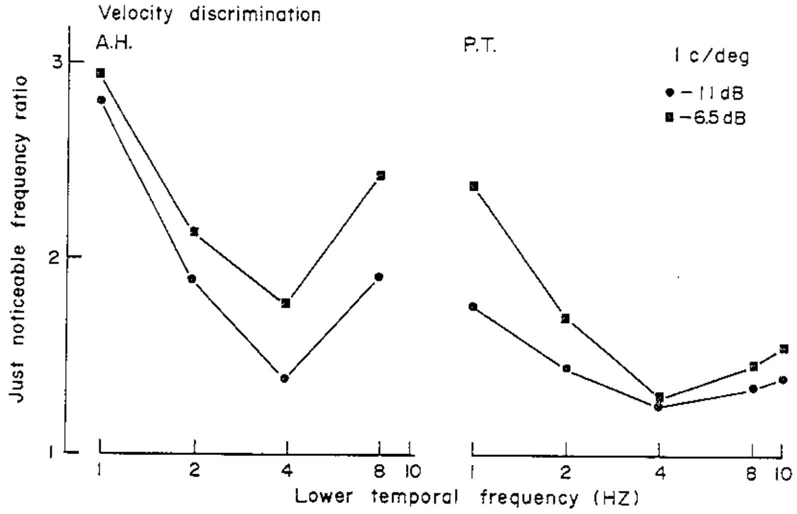

Fig. 1. Velocity discrimination at 1 c/deg. Subjects: A.H. and P.T. Data shown for 6.5 and 11.0 dB above detection threshold.

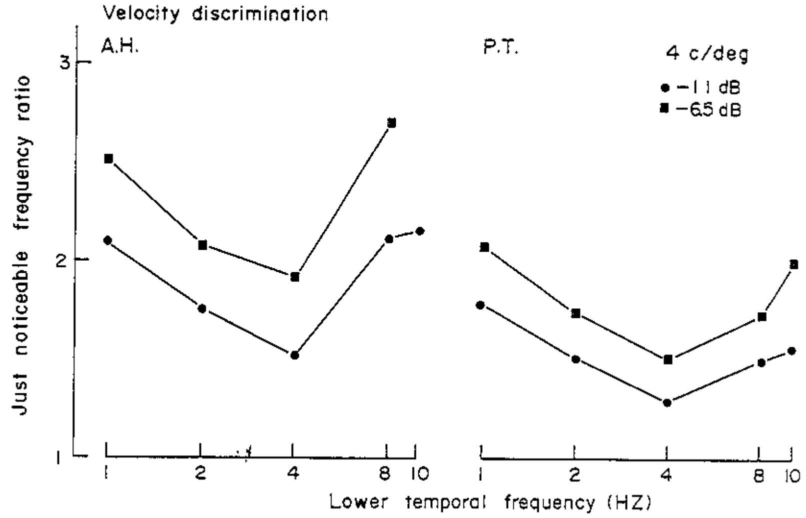

Fig. 2. Velocity discrimination of 4 c/deg subjects: A.H. and P.T. Data shown for 6.5 and 11.0 dB above detection threshold.

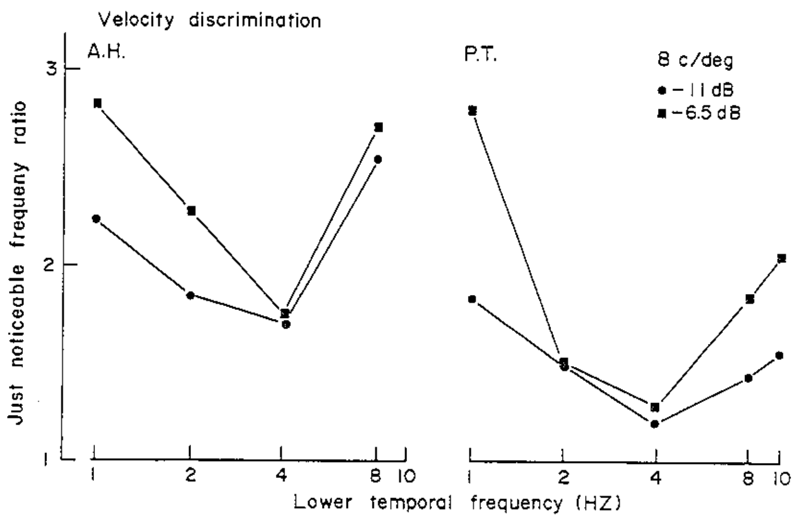

Fig. 3. Velocity discrimination at 8 c/deg subjects: A.H. and P.T. Data shown for 6.5 and 11.0 dB above detection threshold.

thought of as analogous to the comparison of directionally specific channels envisaged by the "Ratio model" of the movement aftereffect, (Exner, 1894; Sutherland, 1961). However, other types of interaction are clearly possible; Erickson (1968), discussing "non-topographic" coding of this kind suggests that discrimination would be greatest when the sum of the rates of change in the two separate channels was greatest. A third possibility is described by Boynton (1979) who describes wavelength discrimination as reflecting the rate of change of sensitivity of independent mechanisms, the wavelength j.n.d. being determined by the fastest changing mechanism at that wavelength. This "independent" model does, however, allow the possibility of probability summation between channels.

All three of these models can predict that discrimination is most acute around the point where the channels cross in their sensitivities, provided that the sensitivity profiles of the channels are chosen appropriately. If we can determine the true profiles then the data presented here may help answer the question of how their outputs are combined to signal rate of movement.

CONCLUSIONS

The investigation of the discriminability of moving gratings both at and above detection threshold suggests that the rate of movement is coded by just two temporal frequency channels. The manner in which the output of these channels are combined remains an open question. It must also be borne in mind that the present study has not investigated high temporal frequencies; Mandler (personal communication) has data from similar experiments employing flickering rather than moving stimuli to suggest a third, high temporal frequency channel, and close examination of data from Pantle (1978) suggests that suprathreshold movement discrimination improves at high temporal rates, again suggesting a further temporal channel. Whether perceived rate of movement is coded by two or three channels, the important point is that the number is clearly small.

The suprathreshold discrimination results show a similar pattern at each of the 3 spatial frequencies investigated, the greatest sensitivity always being at 4 c/sec. This finding, which reproduces the pattern of results reported by Pantle (1978), suggests that movement channels are tuned for temporal frequency rather than for velocity. This conclusion is at variance with the tuning of velocity aftereffects, Thompson (1980), but is exactly what Marr and Ullman (1981) predict. It should perhaps be noted that Marr and Ullman list as "Prediction xxiii" of their model: "If speed (and not direction) is the only available discriminant, separation should be difficult." Without some quantification of the degree of difficulty required this will be a hard prediction to satisfy; the results of the present study indicate rather poor discrimination, but some others, notably Pantle (1978), have shown velocity discrimination which compares favourably with spatial frequency discrimination, (see Campbell *et al.*, 1970).

Now that it seems likely that rate of movement is coded by few temporal frequency channels it may be possible to determine how their outputs are combined to encode velocity of movement in the real world.

Acknowledgements—These results were first presented to the Association for research in Vision and Ophthalmology, Sarasota, May 1982. My attendance at that conference was made possible by the generosity of the University of York and by a travel grant from The Royal Society. This research was supported by the Science and Engineering Research Council, Grant No: GR/A 73817. This paper was greatly improved by the comments of the referees, to whom I express my thanks.

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