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Short Communication

The Coherence of Subjective Gratings

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Two differently oriented moving gratings when superimposed, are often seen to move coherently in a direction quite different from that of either grating's. By varying the characteristics of the component gratings researchers have been able to study specific aspects of the motion processing mechanisms in the primate visual system. Here we report the results of experiments performed with a class of subjective gratings. We find that observers perceive coherence and are able to accurately report pattern velocity with our stimuli. These results have implications for some key issues concerning strategies and mechanisms for motion estimation in the human visual system. Copyright © 1996 Published by Elsevier Science Ltd.

Motion perception   Subjective gratings   Plaids

INTRODUCTION

Our ability to estimate the motion of complex visual patterns is, unarguably, of great adaptive significance. It allows us to interpret and interact with a dynamic environment. However, the question of how this task is accomplished by our visual system is still open to debate. In this paper, we present a few psychophysical experiments that attempt to address some aspects of this question.

EXPERIMENTAL DESIGN

Our experimental paradigm is a variation of the one introduced by Adelson and Movshon (1982). The stimuli they used were plaid patterns formed by superimposing two contrast defined gratings moving in different directions [Fig. 1(a)]. In contrast to this, the plaid patterns that we designed for use in our experiments comprised two moving illusory gratings [Fig. 1(b)]. For most of their extents, the bars of the gratings were not defined by luminance contrast or any other physically measurable visual attributes, but were, instead, illusory. As for other illusory figures (Kanizsa, 1979; Petry & Meyer, 1987), the visual system inferred the presence of the grating contours by partial occlusion information. Both gratings individually afforded the percept of square-waves with low duty-cycles (between 0.15 and 0.2) undergoing uniform oscillatory motion in directions orthogonal to their orientations. The orientation and speed of the component gratings could be varied to yield different pattern velocities. Furthermore, the amplitude of oscillation of each grating was limited to ensure that the illusory intersections of the plaid were never explicitly visible.

Stimuli were generated on a Macintosh Quadra 700 computer equipped with an Apple color monitor that had a resolution of 640 × 480 at 76 dpi. The display programs were written in Symantec's Think C augmented with a graphics library put together at the Harvard Vision Sciences Laboratory (Comtois, 1992). Viewing distance was 80 cm. The circular display subtended 8 deg at this distance. Subjects were asked to fixate at the center of the circular display during the experiments.

Our experiments were designed to study whether subjects perceived coherent pattern motion with illusory plaids and if so, to determine the accuracy with which they could estimate a plaid's velocity. To this end, we tested the performance of four observers on direction and speed matching tasks with illusory plaids. In every trial of the direction matching task, subjects were first presented with an illusory plaid that could move in any one of eight possible directions (evenly spaced about 22 deg apart from each other; see Table 1 for details). This was followed immediately by a conventional contrast-defined grating moving in one of the eight directions. The subjects were instructed to report whether they perceived the plaid pattern as moving coherently and if so, to say whether the plaid and the grating were moving in the same direction.

In the trials of the speed matching task, subjects saw an illusory plaid that moved in a fixed direction with any one of four possible speeds (see Table 1) followed immediately by a grating moving in the plaid's true direction [as computed by the intersection of constraints construction

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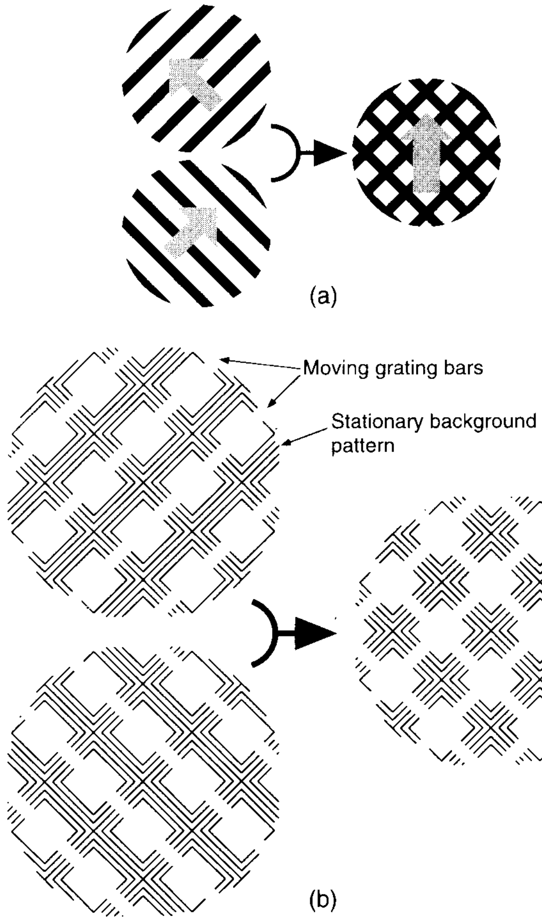

FIGURE 1. (a) The plaid-paradigm: under certain conditions, two independently moving and differently oriented gratings when superimposed are seen to move coherently in a direction different from either of their individual directions of motion. (b) Two illusory gratings and the resulting illusory plaid. The background pattern of nested squares remains stationary.

(Adelson & Movshon, 1982)] with one of the four speeds (the same set of speeds as for the plaids). For every trial during which they saw the plaid pattern as moving coherently, subjects were asked to report verbally whether the plaid and grating speeds were the same or different. Subjects were not given any feedback during the experimental sessions for either of the two tasks.

We also performed a separate set of experiments to determine subjects' direction discrimination thresholds with illusory plaid patterns. Our paradigm followed that of Ferrera and Wilson (1990). Stimuli were presented in a temporal two-alternative forced-choice setting, each interval being 3 sec long. One temporal interval contained an illusory plaid (plaid 1; see Table 1) while the other contained a contrast defined one-dimensional standard. A small angular offset was added to each component of the plaid during every presentation. The standard was made to move in a direction identical to the intersection-of-constraints resultant for the plaid pattern with no offset. Subjects were asked to respond verbally which interval had a greater rightward component of motion.

RESULTS AND DISCUSSION

The first general result to emerge from these experiments was that under conditions like those required for the coherence of conventional contrast defined gratings, viz., similarity of speeds and duty cycles, illusory gratings were perceived to cohere strongly [Fig. 2(a)]. Second, subjects performed very well on our direction and speed matching tasks [Fig. 2(b) and (c)], suggesting thereby that they could quite accurately recover pattern motion velocity of illusory plaids.

In the experiments designed to determine direction discrimination thresholds, we found that subjects re-

TABLE 1. Parameters for the plaid patterns used in our experiments

	Component 1		Component 2		Resultant	
Plaid No.	Speed (deg/sec)	Direction (deg)	Speed (deg/sec)	Direction (deg)	Speed (deg/sec)	Direction (deg)
1	±0.87	45.0	±0.87	135.0	±1.23	90.0
2	±0.51	0.0	±1.26	90.0	±1.36	67.9
3	±1.22	0.0	±1.22	90.0	±1.73	45.0
4	±1.26	0.0	±0.51	90.0	±1.36	22.1
5	±0.87	45.0	±0.87	315.0	±1.23	0.0
6	±1.26	0.0	±0.51	270.0	±1.36	337.9
7	±1.22	0.0	±1.22	270.0	±1.73	315.0
8	±0.51	0.0	±1.26	270.0	±1.36	292.1
9	±0.36	0.0	±0.36	90.0	±0.51	45.0
10	±0.73	0.0	±0.73	90.0	±1.03	45.0
11	±1.33	0.0	±1.33	90.0	±1.88	45.0
12	±2.83	0.0	±2.83	90.0	±4.00	45.0

The spatial frequency of all gratings with orientations of 0 or 90 deg was 0.5 c/deg while gratings oriented at 45 or 135 deg had a spatial frequency of 0.33 c/deg. The ± signs in the speed columns are meant to indicate the oscillatory motion of the gratings and the resultant plaids. The amplitude of oscillation of the different gratings ranged from 0.7 to 1.1 deg (the precise values were set so as to ensure that the grating intersections were never rendered explicitly visible by overlapping with the background pattern). In the direction columns, 0 deg refers to the horizontal right. Angles increase counter-clockwise.

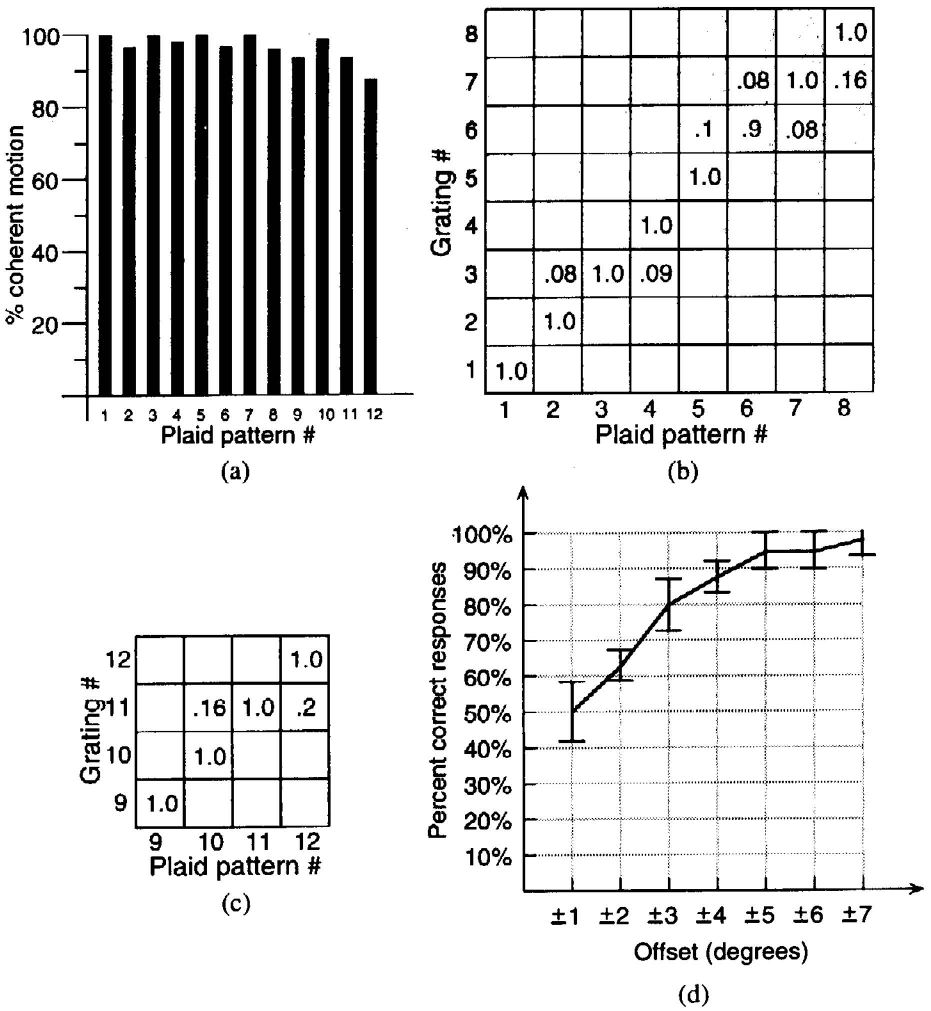

FIGURE 2. Results with illusory gratings. (a) Coherence statistics (over all subjects) for the illusory plaid patterns used in our experiments. Almost all patterns were seen to cohere strongly by the subjects. (b) Results of the direction matching task averaged over four subjects. The entries in the cells of the grid show the fraction of trials (three per subject) during which the subject reported a match in the directions of the corresponding plaid-grating pair. Blank cells denote scores of 0.0. (Grating No. i was designed to have the same direction as plaid No. i. The results of a subject who never made any errors of judgement would, therefore, comprise of 1.0 along the diagonal and 0.0 everywhere else.) (c) Results of the speed matching task averaged over four subjects. The entries in the cells of the grid show the fraction of trials (three per subject) during which the subject reported a match in the speeds of the corresponding plaid-grating pair. (d) Results of the experiment to determine direction discrimination thresholds, averaged across all four subjects. Subjects' performance is well above chance (> 75%) beyond an offset of about 2.5 deg. Each subject was presented with ten trials at each offset level.

sponded with well above-chance accuracy (75%) beyond an offset of 2.5 deg (averaged across all four subjects) [see Fig. 2(d)].

These demonstrations of subjects' accurate pattern motion estimation for illusory plaids have some important implications. We discuss a few next.

The first implication concerns the oft debated issue of how pattern motion velocity (direction and speed) is computed. Two basic schemes have been proposed to address this issue. The first relies on the presence of distinctive localized image features such as grating intersections which may be tracked to straightforwardly recover their (and the overall pattern's) motion (Lorenceau & Gorea, 1989; Rubin & Hochstein, 1992). The second scheme involves integrating the separately estimated ambiguous motion estimates for the two gratings (Adelson & Movshon, 1982; Hildreth, 1984; Welch, 1989; Mingolla *et al.*, 1992). There is no clear consensus as to which of these two schemes is actually used by the primate visual system. The question is made especially difficult by the fact that the most widely accepted scheme for integrating component motions (Adelson & Movshon, 1982) produces identical pattern velocity predictions as the intersection tracking scheme for conventional plaid stimuli.

For illusory plaids, however, the predictions of the feature tracking and component motion integration schemes regarding the ability of an observer to estimate pattern motion can be expected to diverge. Ignoring, for now, the possibility of tracking illusory features, it may be argued that since an illusory plaid has no explicit localized features moving unambiguously with the

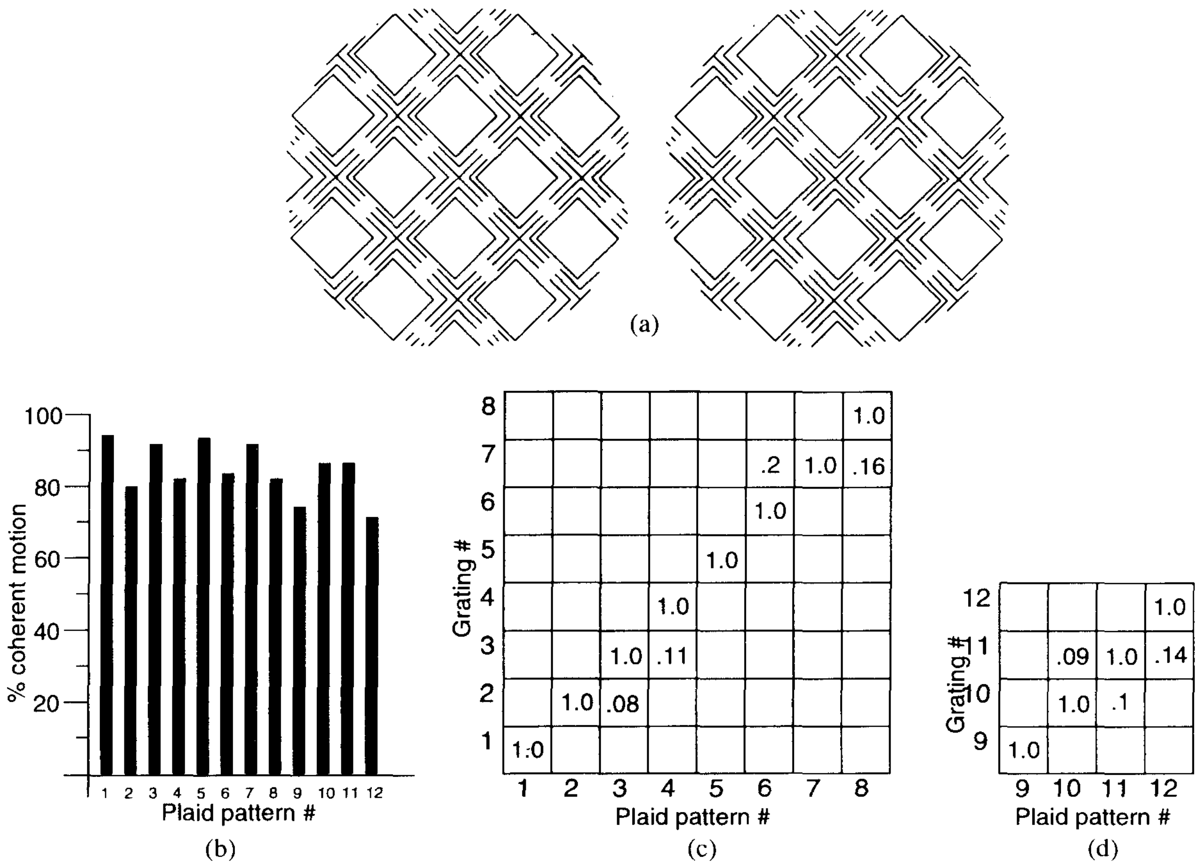

FIGURE 3. (a) The modified plaid pattern shown here as a stereo-pair (for cross-fusers). (b) The incidence of coherence dropped a little following the modification. (c) and (d) Results from the direction and speed matching tasks, respectively, averaged across four subjects over trials during which they reported plaid coherence. Performance is comparable to that obtained with the unmodified stimulus [see Fig. 2(b) and (c)].

pattern velocity, a feature tracking scheme would predict that an observer would be unable to recover the plaid's velocity. The component motion integration scheme, on the other hand, predicts no such handicap. Our experimental results demonstrating that observers are indeed able to accurately estimate an illusory plaid-pattern's velocity argue in favor of the component motion integration scheme.

These results, however, do not rule out the possibility of the visual system tracking "illusory features"—the subjective intersections of our plaid patterns. To test for this possibility we ran our experiments with the stimulus shown in Fig. 3(a). This stimulus comprised an illusory plaid overlaid in depth with a mosaic of opaque patches that destroyed the percept of illusory extensions of the grating bars. The different segments of the bars could now only be linked amodally. Subjects were shown this stimulus in stereo. As Fig. 3(b), (c) and (d) show, while the overall incidence of coherence dropped slightly in this case, subjects could still accurately recover the pattern velocity for the trials in which they saw the plaid moving coherently.

The drop in the incidence of coherence suggests a weakening of the grouping information in the stimulus. A modal presence of the grating bars' intersections apparently is more effective at inducing the visual system to group the component motions than an amodal presence. We can generalize this observation and suggest that for conventional contrast defined patterns too, the visual system might use the localized features as providers of grouping information. This idea is consistent with the experimental reports of Stoner *et al.* (1990); Stoner & Albright (1992a) who found that the luminances of a plaid pattern's intersections determined whether or not the motions of the component gratings were perceptually grouped into a coherent motion.

What about the rather roundabout possibility of the visual system first using the components to estimate the positions of amodal features and subsequently tracking such features? Indeed, our results do not provide a definitive resolution of this issue. However, the limited precision with which amodal features can be localized and tracked (Steinbach, 1976) argues against this possibility in the light of the very precise direction discrimination performance we have observed with illusory plaids.

Taken together, while our results do not rule out the possibility of the visual system tracking localized features when they are available, they do suggest that the presence of such features is not a necessary prerequisite for pattern motion estimation; the visual system can recover pattern motion velocity by integrating ambiguous component motions. The localized features, however, do seem to play a role in the integration process

FIGURE 4. A plaid pattern made of contrast balanced subjective gratings. Observers often perceive such patterns as moving coherently and are able to accurately estimate the pattern velocity.

by providing information that determines which, and whether, component motions are to be grouped together.

On a related note, these results also present an interesting challenge to the idea that pattern motion must be computed from the motion of components (such as those associated with the plaid intersections) that are derived from the luminance distribution by a simple nonlinear transformation (Wilson *et al.*, 1992).

It is important to emphasize that although we have attempted to make a distinction between the two strategies for pattern motion recovery, they are not mutually exclusive. The visual system might employ both these schemes with the attendant gains in robustness and possibly accuracy at the expense of redundancy. Precisely how the two schemes might be used cooperatively is an interesting and important question in its own right.

Another implication of our experimental results concerns the physiological substrate underlying these perceptual phenomena. That the motions of illusory gratings can be integrated into coherent pattern motion (coherence is obtained even with gratings comprised of completely contrast balanced contours of the kind shown in Fig. 4) hints at a relationship between cortical areas V2 and MT. The former has been shown to have a large population of cells, many of them directionally selective, responsive to subjective contours (von der Heydt & Peterhans, 1989; Peterhans & von der Heydt, 1989, 1991) while the latter is believed to play a role in global motion integration (Movshon *et al.*, 1985; Newsome & Pare, 1988). We wonder if it is possible that MT integrates the responses of V2 cells much as it does the responses of directionally sensitive cells in V1 (Movshon *et al.*, 1985). This possibility is consistent with the conclusions drawn by Stoner and Albright (1992b) from their studies of form-cue invariance in the responses of MT cells.

Sample sequences on disk

Readers can obtain some of the sequences used in the experiments reported here by writing to the author via regular mail or the internet [sinha@ai.mit.edu].

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