Direction-of-motion discrimination with complex patterns: further observations

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Moving one component of a stimulus comprising two sinusoidal gratings of the same orientation sometimes results in mistaken judgments of the direction of motion. If the component with the higher spatial frequency moves and the stimulus is presented briefly, observers report motion in the direction opposite that which actually occurs. The illusion, or backward, motion appears whether the movement producing it occurs smoothly or as a discrete jump at the midpoint of the stimulus presentation. At durations at which motion appears reversed, smooth and discrete motion are indistinguishable. Measurement of the speed of the illusory motion by a cancellation technique permits comparison with results from classical induced-motion paradigms; the classical effect, obtained with spatially separated components, is smaller but in the same direction as the errors in perceived direction of motion that we measure. We suggest that the errors in judging the direction of motion may result from interactions among motion detectors tuned to the different spatial-frequency components of the stimulus.

INTRODUCTION

The direction in which a briefly presented, vertical sinusoidal grating appears to move can be reversed by the addition of a static component of lower spatial frequency. In the presence of a component of lower spatial frequency, the combined pattern appears to move in a direction opposite that in which the moving component actually moves; the same motion viewed without the lower-spatial-frequency grating is seen correctly.

The illusion occurs when the stimulus duration is brief—less than approximately 100 msec. At durations greater than 200 msec, the higher-frequency grating is seen correctly as moving in the direction in which it actually moves—even in the presence of a static low-frequency grating. The short stimulus durations required to produce the effect suggest the operation of what is often termed the low-level motion system. However, current models of low-level motion processing do not readily predict the effect, and even our suggested modifications of the models to allow them to predict the illusion are not particularly compelling.

It seemed possible that a single-channel, gradient-based motion-detection system might account for the illusion. The mechanism was developed from that proposed by Limb and Murphy and by Fennema and Thompson for extracting regions with different velocities from successive frames of video displays. In this paper, we first show that system has characteristics different from those of our observers and that it can therefore be rejected as a model of the mechanism underlying human performance.

Then, to determine the magnitude of the illusory motion, we measure the amount and direction of real motion required to cancel it. Preliminary measurements were not inconsistent with the notion that, at short durations, judgments of the direction of motion are relative judgments in which the relative motion is ascribed to the lower-frequency component. But data for different observers were inconsistent. Further measurements, although not contradictory, reveal a more complicated picture.

METHOD

The stimuli and experimental procedures were identical to those described by Derrington and Henning. Vertically orientated spatial patterns were generated on a television display (Joyce Electronics, Cambridge) by using a computerized version of the method of Schade. The cross-sectional luminance profile of the (one-dimensional) stimuli consisted of the sum of one or more sinusoids of the same orientation. Each component could be made to move independently to the left or to the right and at different speeds. The display subtended 7.5 by 6.25 deg at the observers' eyes, and the presentation of a stimulus did not alter its mean luminance (180 cd/m²).

Each component of the stimulus was generated by reading numbers from a list, stored in a PDP 11/73 computer, to a 12-bit digital-to-analog converter. The digital-to-analog converters generating the analog signal for the 95-kHz raster were altered on every line, and approximately 500 lines were displayed on each frame. Smooth motion of any component was introduced by changing the starting position in its list by a small amount at the beginning of each frame (every 8 msec). If a single step displacement was required, the starting position was changed at the beginning of a frame in the middle of a presentation. In most of our experiments, the two components of the stimulus were added together and the sum used to modulate the contrast of the display. However, in one experiment, analog switches synchronized with the
vertical scan were used to switch between the two components so that one component appeared in a band across the center of the display and the other in bands at the top and bottom.

The duration of the stimuli was manipulated by adjusting the time constant, $\sigma$, of the Gaussian temporal envelope (truncated at 1.024 sec) that modulated the contrast of both components of the stimulus.

The observers (usually the authors) were required to discriminate between leftward and rightward motion in a standard two-alternative forced-choice task: A stimulus in which one or more of the components moved in some direction was presented in the first observation interval of each trial. After a pause, and in the second observation interval of the trial, the direction of motion was reversed. The observer’s task was to press a key to indicate the interval in which the stimulus moved leftward; a second press began the next trial. Different types of stimulus presentation were randomly interleaved, and the number of correct responses was recorded separately for each type of stimulus.

**RESULTS AND DISCUSSION**

Experiment I: The Effects of Relative Phase

The stimulus comprised two gratings, each with 12% contrast: a static (nonmoving) grating having a spatial frequency of 1 cycle per degree of visual angle (c/deg) and a grating of 3 c/deg that changed location in a single step at the center of the Gaussian temporal envelope that determined the duration of the (compound) stimulus. The 3-c/deg grating moved in one direction in the first observation interval and in the opposite direction in the second; the observers’ task was to indicate the interval in which leftward motion occurred. The displacement step imposed on the 3-c/deg grating was one quarter of its spatial period.

Two different temporal envelopes were used: long duration ($\sigma = 0.27$ sec) and short duration ($\sigma = 0.014$ sec). The durations were chosen because observers correctly report the direction in which the 3-c/deg grating moves at the longer duration but, at the shorter duration, see motion in the direction opposite that in which the moving component actually moves. In neither case does the direction of apparent motion depend on the relative phase of the moving and static components.

That the illusory “backward” motion does not depend on the relative starting phase of the two components is inconsistent with the notion that the observers use a mechanism analogous to our modification $^1$ of the gradient-based model of Fennema and Thompson. $^{10}$ In a gradient-based motion detector, velocity estimates over the surface of the display are derived locally from the ratio of the rate of change of luminance with time to the rate of change of luminance with distance. With our two-component stimuli, the velocity estimates depend on location within the stimulus but, over most of the display, can be made to predict reversed motion by assuming the internal representation of the component of moving in the direction opposite that in which the moving component actually moves. In neither case does the direction of apparent motion depend on the relative phase of the moving and static components.

From observation interval to observation interval the spatial phase of the static 1-c/deg grating was chosen randomly from a set of eight equally likely phases equally spaced from 0 to 360 deg. The principal variable manipulated was the phase of the 3-c/deg grating, which was fixed at one of eight 0 to 360 deg. The principal variable manipulated was the phase of the 3-c/deg grating, which was fixed at one of eight equally likely phases equally spaced from the center of the display and the other in bands at the top and bottom. The principal variable manipulated was the principal variable manipulated was the phase of the 3-c/deg grating, which was fixed at one of eight equally likely phases equally spaced from the center of the display and the other in bands at the top and bottom.

Figure 1 shows the number of correct responses as a function of the phase of the 3-c/deg grating—Fig. 1(A) for observer AH and Fig. 1(B) for observer AMD. Open symbols show the results obtained with the longer stimulus duration; filled symbols show the results with the shorter duration. It is clear that the relative phase of the moving component has little effect on the apparent direction of motion. As in the results reported previously, $^1$ the motion of stimuli exposed for the longer duration is correctly perceived, whereas stimuli exposed for the shorter duration are consistently seen as moving in the direction opposite that in which the moving component actually moves.
higher spatial frequency to have much less contrast than that of the lower-frequency component. Under these conditions, the model predicts that direction-of-motion judgments should depend strongly on the relative phase of the two components, and the phase dependence derived from the model is indicated in Fig. 2.

The ordinate of Fig. 2 shows the decision variable derived from the model as a function of the starting phase of the 3-c/deg grating. Values greater than zero correspond to correctly seen motion; values less than zero correspond to illusory or backward motion. Figure 2 demonstrates that the model predicts that direction-of-motion discrimination should show a strong dependence on phase, a dependence that is clearly not part of our observers' behavior. We therefore reject the model.

One characteristic of the steplike motion used in this experiment is that it appears to be smooth and continuous at the short durations for which the illusory motion occurs. Experiment II established and measured this effect.

Experiment II: Discrimination of Smooth from Abrupt Motion

The stimuli in Experiment II were simple sinusoidal gratings of either 1 or 3 c/deg. In one observation interval, the grating moved abruptly either leftward or rightward by one quarter of its spatial period. The motion occurred as a single jump at the center of the Gaussian temporal envelope that determined the stimulus duration. In the other observation interval, the stimulus moved smoothly (that is, in small, equal spatial steps made every 8 msec at the beginning of each frame). The observers’ task was to indicate the interval in which the smooth motion had occurred. To prevent our observers from attempting to perform the discrimination on the basis of the distance traveled by the stimulus during the observation interval, the speed of the smoothly moving grating was made inversely proportional to the duration of the grating. Then, to remove any potential cue resulting from failure to match velocities in the two observation intervals, two speeds that differed by a factor of 5 were used at each duration. Speeds corresponding to temporal frequencies of 12.2 and 2.44 Hz were used at the shortest duration. The success of these precautions was indicated by the fact that discrimination of smooth from abrupt motion was independent of speed at each duration; consequently, the data for the two speeds have been combined.

Figure 3 shows the percentage of correct discriminations based on 100 trials as a function of the time constant of the temporal envelope. Data for the two observers are shown in separate panels: open circles show the results obtained with 1-c/deg gratings; open diamonds, the results with 3-c/deg gratings. The data indicated by the filled symbols show each observer’s performance in discriminating direction of motion with single jumps of one quarter of the period of a 3-c/deg grating in the presence of a static 1-c/deg grating (from Fig. 4 of Ref. 1). The results confirm our informal observations; the observers were unable to discriminate smooth from discrete motion at signal durations determined by time constants less than ~50 msec, and it is at these durations that the illusory motion predominates.

A common explanation of our failure to make a discrimination is that the information on which the discrimination might be based is not available to the observer either through lack of sensitivity or through masking.13-16 If we assume that a motion-detection system has no information about stimuli that produce no changes in luminance over time, then the result implies that the motion system cannot discriminate a temporal motion impulse from a rectangular pulse of the same area lasting ~100 msec. This corresponds approximately to the blur time inferred by Burr and Ross.”

Fig. 2. Effect of spatial phase on the decision variable of the modified gradient model as a function of the spatial phase of a moving 3-c/deg component measured relative to the peak of the static 1-c/deg component. Positive values of the decision variable indicate motion in the same direction as that of the moving component of the pattern; negative values indicate motion in the opposite direction.

Fig. 3. Discrimination between discrete and continuous motion for 1-c/deg (open circles) and 3-c/deg gratings (diamonds) as a function of the time constant of the Gaussian temporal envelope. The filled circles, for comparison, show direction-of-motion discrimination of a stimulus comprising a static 1-c/deg grating and a 3-c/deg grating that changes phase by 90 deg at the midpoint of the observation interval.
and to what might be expected from the bandwidth of either of the two low-temporal-frequency mechanisms derived from flicker-frequency discrimination experiments\textsuperscript{18,19} or inferred from flicker-adaptation studies.\textsuperscript{20}

Our observers found it difficult to estimate the velocity of the illusory motion other than to note that it seemed brisk. Experiment III measured the velocity of the illusory motion by adjusting the velocity of the lower-frequency component to find the speed at which the observers were unable to specify the direction of motion.

**Experiment III: Canceling the Illusory Motion**

The stimulus had two components with the spatial frequencies and contrasts used in Experiment I. The 3-c/deg grating moved smoothly at a speed of 4 deg of visual angle per second (12.2 Hz), and the speed of the 1-c/deg grating was manipulated. The direction of motion of both gratings was changed between the two observation intervals of each trial, but their speeds in the two intervals were the same. Motion of the 1-c/deg grating in the same direction as the 3-c/deg grating is indicated by positive speed or temporal frequency; motion in the opposite direction, by negative speed or temporal frequency. Two different durations were used: long ($\sigma = 0.27$ sec) or short ($\sigma = 0.014$ sec).

The results for each observer are shown separately in the two columns of Fig. 4. In the two left-hand panels (short durations) the number of trials on which the observers reported seeing motion in the direction in which the 3-c/deg grating moved is plotted as a function of the temporal frequency of the 1-c/deg grating. Negative temporal frequencies indicate speeds of the 1-c/deg grating moving in the direction opposite that of the 3-c/deg grating; positive temporal frequencies indicate motion in the same direction as that of the 3-c/deg grating.

For short durations, it is clear that the observers require the 1-c/deg component to move in the same direction as the 3-c/deg grating in order to cancel the apparent motion. The results obtained with the longer stimulus duration are shown in the two right-hand panels (note the 10-fold increase in the scale of the abscissa). The data for longer durations resemble those at short durations, but the temporal frequency of the 1-c/deg grating that produces equal numbers of leftward- and rightward-moving responses is much closer to zero.

The smooth curves are least-mean-squares fits of the cumulative normal distribution to the data. The fits were calculated by probit analysis. We take the mean of the cumulative Gaussian as the temporal frequency of the low-frequency grating that results in equal numbers of leftward and rightward motion and call that temporal frequency the canceling frequency.

There are some similarities between aspects of the illusory motion that we have been studying and the phenomena of induced motion. Before considering the implications of the cancellation experiment, we compare our results with those obtained in a conventional induced-motion paradigm.
Experiment IV: Induced Motion

In Experiment IV the display was divided into three horizontal strips, each of which subtended 2 deg of visual angle in height. Gaps of 0.3 deg separated the top and bottom strips from the central strip. The stimulus in the top and bottom strips of the display was the inducer—a 3-c/deg grating moving leftward in one observation interval and rightward in the other at a speed of 4 deg of visual angle per second (a temporal frequency of 12.2 Hz). The stimulus that filled the center section of the display (1-c/deg grating) was the test stimulus; we manipulated its speed. The direction of motion was reversed between the observation intervals of each trial, and the observers were required to report the direction in which the 1-c/deg grating moved. Two stimulus durations (\( \sigma = 0.014 \) and \( \sigma = 0.27 \) sec) were used.

Figure 5 shows the number of trials on which the observers reported the 1-c/deg grating to be moving in the same direction as the 3-c/deg grating (inducer) as a function of the temporal frequency of the 1-c/deg grating. Motion in the split-screen case at short durations is in the same direction as the illusory motion with superimposed stimuli, but, measured in terms of the canceling motion, it is a little more than a factor of 2 weaker. There is almost no induced motion at the longer stimulus duration. This result is consistent with the work of Levi and Schor.\(^{21}\)

Figure 6 summarizes the data of Figs. 4 and 5. It shows the temporal frequency of the 1-c/deg grating at which the observers are unable to discriminate direction of motion as a function of the time constant of the Gaussian temporal window. The insets illustrate one frame of the two display types. At the longer duration, there is little induced motion either with the whole field or with the split-screen display.

At the shorter duration, the speed of the induced motion with the split-screen is about 2 deg of visual angle per second. This is less than one half of the speed obtained when the test and the inducer were superimposed. With superimposed components, the induced motion has a velocity (4.8 deg/sec) almost equal to that of the 3-c/deg grating (4.07 deg/sec).

The similarity of the speed of the moving component and the measured speed of the illusion suggests that the observers might be judging relative motion: First, the speed of the 1-c/deg grating that canceled the motion induced by the moving 3-c/deg grating was nearly the same as that of the 3-c/deg grating. Second, the canceling 1-c/deg grating moved in the same direction as the 3-c/deg grating; that is, cancellation occurred when there was almost no relative motion between the components of the stimulus. This observation might be taken to suggest either that the low-level-motion system signals relative motion or that motion information for short-duration signals is interpreted by the low-level-motion system as if it were information about relative motion.

In order to explore the notion that our observers might, in effect, be judging relative motion, we extended the cancellation experiment by using 2-, 3-, and 6-c/deg gratings as the
higher-frequency components with lower-frequency components of 0.25, 1, 2, 3 and 4 c/deg. The temporal frequency of the moving high-frequency component was 12.2 Hz in all cases, and both high- and low-frequency components were presented within a brief Gaussian envelope ($\alpha = 0.014$ sec).

Figure 7 shows the temporal frequency (in hertz) of the lower-frequency component corresponding to equal numbers of leftward- and rightward-moving judgments (determined from the 40-observation-per-point psychometric functions by probit analysis) as a function of the spatial frequency of the lower-frequency component. The parameter is the spatial frequency of the higher-frequency grating.

On the coordinates of Fig. 7, a (one-dimensional) test object moving at a constant velocity has its spatial-frequency components on a straight line through the origin. This is simply because an object moving at constant velocity past a point in space produces temporal frequencies that are proportional to the spatial frequencies that constitute the object. The slope of the line is determined by the direction and speed of the motion. Consequently, test objects moving at the same velocity as the 2-, 3-, and 6-c/deg inducing gratings should lie on the solid, short-dashed, and long-dashed lines, respectively. Our data do not fall exactly on those lines, but, for one branch of each set of data at least, they are not sufficiently discrepant to justify our rejecting out of hand the notion that the observers judge relative motion and attribute the resulting motion to the lower-frequency object.

**DISCUSSION**

The apparent reversal in the direction of motion of briefly presented compound stimuli does not depend on the relative phase of the components of the stimulus. Thus, since the gradient-detection model that we had tentatively considered in a previous paper predicts phase dependence, the model must be rejected. Furthermore, the fact that the reversed motion occurs when the moving and static components are separated in space makes it possible to speculate...
that the percept may perhaps result from the combination of the outputs of different mechanisms responding to the different components. We shall consider two possible reasons for the reversal; neither of them is particularly compelling, but each merits some consideration. The first is that the observers track the moving component in some way. The second concerns the way in which the determination of the speed of motion might depend on estimates of temporal frequency obtained at different spatial frequencies.

**Tracking the Moving Component**

Since the illusory motion occurs for stimuli durations less than 50 msec and since eye movements have at least a 90-msec latency,\(^2\) it seems unlikely that eye movements play a crucial role in producing the illusion, although they may, of course, play a role in preventing it. Nonetheless, the observations of the cancellation experiments are consistent with the assumption that the observers change their frame of reference (as if they attempt to track the moving 3-c/deg grating) and then report the motion of the 1-c/deg grating relative to the moving frame of reference. In this explanation, the illusion is caused by a mismatch between the moving frame of reference and the position of the eyes; it occurs because the frame of reference begins to move in anticipation of a (tracking) eye movement. This notion is suggested by the recent studies of Burr and Ross.\(^7\) At longer durations the mismatch is removed either because the tracking movement takes place and the eyes catch up with the moving frame of reference or because the tracking movement does not occur and the frame of reference is corrected.

One difficulty with this explanation is that it provides no obvious explanation of the spatial-frequency selectivity of the phenomenon, that is, no explanation why the higher spatial frequency should be so much more effective in shifting the frame of reference than the lower. We have no supporting evidence for the moving-frame-of-reference conjecture. An alternative account of the phenomenon consistent with its spatial-frequency dependence is suggested by a second explanation.

**Temporal Frequency as a Function of Spatial Frequency**

In the retinal image of a rigid (one-dimensional) object moving with constant velocity, the temporal frequency of each spatial-frequency component is given by the product of the object's velocity and the spatial frequency of the component. Thus velocity can be estimated either directly for any component or indirectly from the slope of the line relating temporal frequency to spatial frequency (see Fig. 6). In a real object, for which the signal associated with any one component will be weak, we might even expect that the slope, estimated from many spatial-frequency components, would provide a more reliable velocity estimate than any single component. Velocity estimates based on local slope in the temporal-frequency by spatial-frequency plane might lead to our illusory motion through misestimation of either spatial or temporal frequency, the latter being the more likely. First, note that in our stimuli there is a conflict: Because there are two different motions, the temporal frequencies do not fall on a constant-velocity line in the temporal-frequency spatial-frequency plane. The system successfully resolves the two motions at long durations but fails with brief stimuli. It is possible that the illusory motion is seen at short durations because briefly presented stimuli have broad spectra that affect temporal-frequency estimates at each spatial frequency and consequently change the slope of the line from which velocity estimates may be made. If the misestimation were sufficient to cause the slope of the line to change sign, then we should expect reversed motion. Detailed consideration of the mechanisms available for estimating temporal frequencies\(^5,6,16-20\) do not preclude this explanation.

The complete answer to motion probably lies in the fact that motion, like color, is extracted by a finite number of systems. The stimulus for the illusory motion with brief stimuli results in the motion system's producing the motion analog of a metameric match. It is striking only in that the motion perceived is different in direction from that which actually occurs. The problem of inferring the set of mechanisms from which our brief stimuli and long-duration stimuli moving in the opposite direction produce the same responses, however, is not easy. Nevertheless, the suggestion at least has clearly testable implications.

**SUMMARY**

1. A stimulus that is the sum of a moving sinusoidal grating of 3 c/deg and a static 1-c/deg sinusoidal grating appears to move in the direction opposite that of the moving component if the stimulus duration is short.

2. The fact that direction-of-motion discrimination shows no dependence on the relative starting phase of the component stimuli allows us to reject models of the low-level human motion system based on a simple gradient-based motion detector: Estimates of motion direction made by such a device show a strong dependence on phase; human observers do not.

3. The stimulus duration below which our observers are unable to discriminate smooth from abrupt motion suggests that motion may be determined by mechanisms with temporal bandwidths of ~10 Hz. This is the bandwidth of two of the temporal channels estimated from flicker-frequency discrimination experiments\(^17,18\) and from flicker-adaptation studies.\(^19\)

4. The reversed motion can be canceled by moving the initially static low-spatial-frequency component in the same direction as the high-spatial-frequency component. The temporal frequency required to cancel the motion is less if the two components are presented in different parts of the display and is negligible if the stimulus duration is long.

5. The temporal frequency required to cancel the reversed motion varies when the spatial frequencies of the two components are changed. Only when the effect is at its largest is the velocity of the canceling motion comparable with the velocity of the motion inducing the reversed motion.

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REFERENCES AND NOTES

12. Contrast \( c(t) = C_{max} \exp[-t^2/(2 \cdot \sigma^2)] \).