Vision Res. Vol. 32, No. 1, pp. 73–80, 1992
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0042-6989/92 $5.00 + 0.00

Misdirected Visual Motion in the Peripheral Visual Field

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Received 14 January 1991; in revised form 21 May 1991

An object moving against a textured background is accurately perceived when viewed foveally, but when viewed peripherally the object's perceived direction of motion may deviate from veridical by as much as 90 deg. The illusory direction is oblique to the orientation of the background contours, which may themselves be moving or stationary. In several experiments, we examined the boundary conditions for occurrence of the illusion and tested hypotheses concerning its basis. This illusion of perceived direction dramatizes differences in motion processing between the fovea and the periphery.

Motion perception Illusion Direction Periphery Human vision

Seeing the direction in which an object moves, a fundamentally important perceptual ability, occurs effortlessly and very quickly. Yet judging direction of motion is not a trivial accomplishment by the visual nervous system. As evidenced by the so-called aperture problem (Adelson & Movshon, 1982), local motion vectors provide ambiguous information about direction. It is now commonly thought that veridical motion perception, including perceived direction of motion, requires several information processing steps, one local and linear and the other global and non-linear (Bulthoff, Little & Poggio, 1989; Welch, 1989; Ferrara & Wilson, 1990). Here we describe a striking visual illusion of motion, in which the direction of motion of an object moving against a textured background may be misperceived by up to 90 deg. The illusion only occurs with peripheral viewing of the object and when the actual direction of motion is oblique to the orientation of the background contours, which themselves may be stationary or moving. Evidently, the effectiveness of local motion energies present in this kind of display varies with retinal eccentricity, implying regional retinal differences in the implementation of global motion processing.

METHODS

In our studies, visual displays were created on the screen of a monochrome monitor (66.7 Hz frame-rate; 72 dots/inch) under control of a Macintosh computer; the luminance of the screen was 12 cd m^{-2} for dark regions and 150 cd m^{-2} for light regions. The insert to Fig. 1 shows a typical screen display, consisting of a circular patch of square-wave grating with a small rectangular bar overlaying the grating. Using conventional animation techniques, the bar was moved over the center of the grating, which itself was stationary. For most observations, the total spatial extent of the bar's travel was 2.1 deg, with the bar passing through the center of the grating at the center of its path. Speed of motion of the bar was typically 4.2 deg/sec, although this value and the distance traveled are not critical.

RESULTS

The basic illusion

Suppose the contours of the grating are oriented 45 deg anticlockwise and the bar is vertical and moves in a direction 45 deg clockwise (i.e. up and to the right). The bar's direction of motion is accurately perceived when the display is viewed foveally. Viewed peripherally, however, the bar appears to move directly rightward or even downward to the right, with its perceived direction of motion dependent on its retinal eccentricity. When the long axis of the bar is horizontal and it moves upward to the right, it appears to move straight up or up and to the left, again depending on eccentricity. Whether the bar is vertical or horizontal, its trajectory sometimes appears curved, not strictly linear. In fact, observers often report that a bar moving, say, down and to the right appears to move up and to the right (the illusion) but ends up at a position lower than it started. This probably contributes to the curved path of motion sometimes experienced. In all cases, the illusion gradually disappears as the aspect ratio of the bar approaches unity (i.e. its shape becomes more nearly square), a point we shall return to in a subsequent section.

A weakened version of the illusion is also experienced when the background, rather than a grating, consists of a checkerboard pattern comprising black and white

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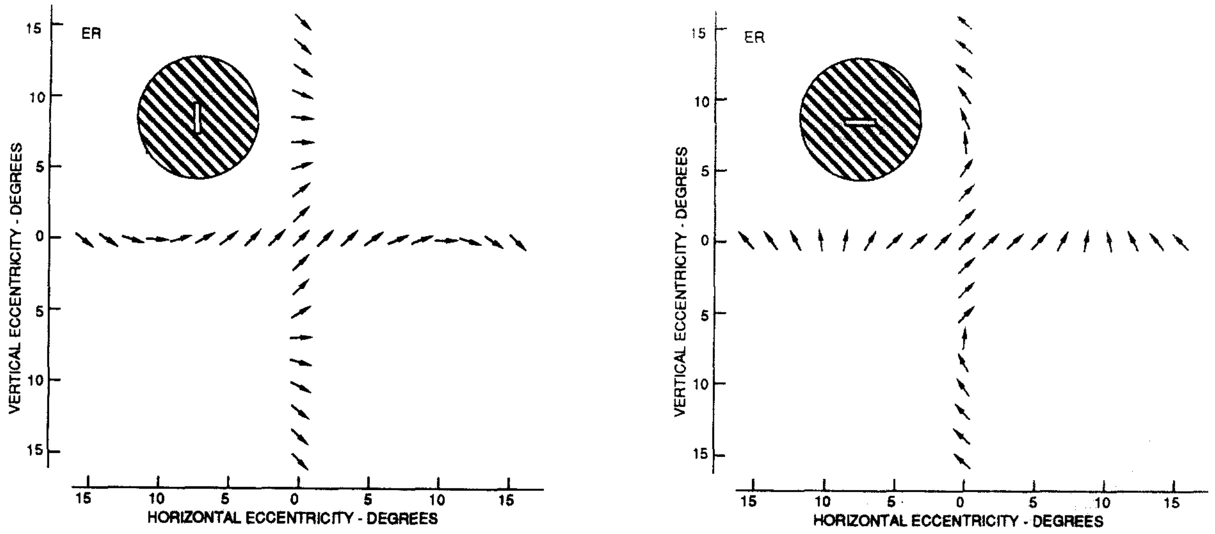

FIGURE 1. Perceived direction of motion of a bar moving across the center of a grating oriented 45 deg anticlockwise from vertical. Perceived direction is specified by the directions in which the arrows point. The ordinate and abscissa give the bar's location in deg in the visual field relative to fixation. In the left panel the moving bar was vertical and in the right panel it was horizontal. The arrow in the center indicates the bar's true motion direction, which was always up and to the right for both bar orientations. Each arrow is the average of ten trials, and these results for observer ER are typical of all results.

squares. When the edges of the checks are oriented vertically and horizontally, the texture behaves like a grating oriented ±45 deg to either side of vertical (i.e. an eccentrically fixated, small vertical bar moving up and to the right appears to move down and to the right). In the Fourier domain, this checkerboard, in fact, has energy at the two major diagonals (DeValois & DeValois, 1988). These gross distortions in peripheral direction perception are not experienced when the background grating is replaced by a uniform gray field or by a field of totally random dots. The color of the bar, however, makes no difference: the illusion is experienced when the peripherally viewed bar is entirely white (without a black surrounding border), entirely black or uniform gray, whereas motion perception is veridical when these different colored bars are viewed foveally.

Finally, the illusion does not depend critically on fixation, aside from the requirement that the moving bar be imaged in the periphery. Besides testing with fixation steady, we have also had observers track a moving, foveally viewed bar whose direction and speed exactly mirrored that of the peripheral bar moving over a background grating. These pursuit eye movements parallel to the true path of motion of the bar do not affect the illusion. Consequently, observers describe that the two targets (which are in fact moving in parallel paths at all times) appear on a collision course when moving in one direction and appear to be on divergent paths when moving in the other direction.

We have shown these basic displays to over 100 individuals, all of whom express amazement at the magnitude and direction of the illusion—it is quite robust and very reliable.* We also have performed several experiments to establish boundary conditions and to test hypotheses concerning the bases of the illusion.

Illusion strength varies with eccentricity

In one experiment, we measured the dependence of the illusion on eccentricity by systematically varying the angular distance between the center of a 7 deg circular test display and a small foveally viewed fixation mark. The stationary background grating was oriented 45 deg anticlockwise from vertical. The moving bar was either vertical or horizontal, and its motion was always 45 deg clockwise (up and to the right). The motion sequence was shown repetitively, with a 0.5 sec pause between repetitions. At the viewing distance of 33 cm, the fundamental spatial frequency of the grating was 1.7 c/deg and the target bar subtended 0.3 × 1.2 deg visual angle. While maintaining fixation on the mark, the observer reported the direction of apparent motion of the bar in terms of the clock time toward which the bar seemed to move. By this notation, the target actually moved toward 1:30 on all trials; a judged value of, say, 3:00 indicated that perceived motion was horizontal and to the right. Fixation was manipulated out to 15.3 deg along each of the four major coordinates. For each fixation position, ten judgments of motion direction were obtained, with the order of fixation and bar orientation varied pseudo-randomly.

Three observers (two naive) participated in this experiment, and all gave essentially identical results; Fig. 1 shows results for one naive observer. The small arrows denote the apparent direction of motion of the bar at various eccentricities. The average SE for each data point was only 2.8 deg, indicating that observers were very consistent in their judgments. Within 3–5 deg of fixation direction of motion is judged more or less accurately (as indicated by the arrows pointing upward to the right), but at greater eccentricities it becomes

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*The first author will mail a Macintosh software demonstration of the illusion to anyone sending an 800 K floppy disk and a self-addressed, stamped mailer.

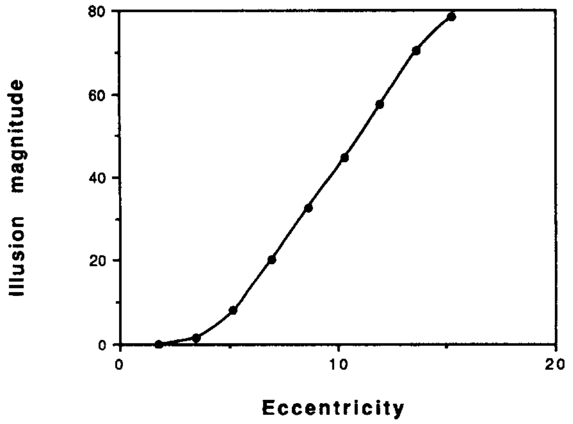

FIGURE 2. Summary graph showing increased illusion magnitude (i.e. deviation of motion path from veridical) as a function of eccentricity. Each data point is the average over all three observers and all visual meridians.

systematically more distorted along all four coordinates in a direction dependent on bar orientation. Figure 2 shows the magnitude of the illusion (angular degrees away from veridical) as the function of eccentricity. Each data point summarizes the results for all three observers and all four visual meridians. The variation in illusion strength with eccentricity is clearly nonlinear. Because of the nature of the dependent variable in these experiments, it is impossible to compare this function to other curves summarizing performance changes with eccentricity (Levi, Klein & Aitsebaomo, 1985).

Illusion strength for different orientations

In a second experiment, we varied the orientation of the stationary background grating, and for each orientation tested eight different directions of motion of a vertical bar (all major axes plus the diagonals). Over trials, observers judged the direction of bar motion by using the computer mouse to place a small marker at the position on a circle (centered on the fixation mark) coinciding with the perceived direction of motion of the bar. Fixation was always maintained so that the center of the background grating was 15 deg into the lower hemifield along the vertical meridian; the bar moved through a 2.4 deg excursion at approx. 2 deg/sec, and the angular dimensions of grating and bar were the same as those given above. Five observers (three naive) were tested, and their averaged results are shown in Fig. 3(a) which plots the difference between actual and perceived directions of motion. As denoted by the cluster of data points at the origin, perception was veridical when the vertical bar moved parallel to the contours of the grating or when it moved straight up or straight down. For other directions of motion, however, perception was in error by up to 90 deg. We shall return to the other data in this figure in a moment.

Illusion under dichoptic stimulation

We modified the computer animation sequence so that a pair of circular backgrounds and/or moving bars could be presented side-by-side on the monitor. By having observers peripherally view this display through a prism stereoscope, it was possible to test for the illusion under conditions of dichoptic stimulation. When the background grating is viewed by one eye and the moving bar by the other eye, the illusion is destroyed—these conditions yield robust binocular rivalry, and when the bar is dominant it moves in the true, not illusory, direction. The bar frequently disappears altogether, leaving just the background grating visible.

Next we presented the background grating and the bar to both eyes, with the bar imaged with 36 min of crossed disparity, causing it to stand out in depth from the background. Despite no longer appearing to travel directly over the background grating, the bar continued to move in its illusory direction in a manner indistinguishable from the zero disparity condition. Reversing the sign of the disparity (36 min uncrossed) caused the bar to appear behind the background grating but had no effect on the illusion. Evidently the neural process underlying this illusion is not sensitive to retinal disparity.

Illusion at different spatial scales

It is well known that spatial resolution varies with retinal eccentricity and that these variations may be attributable to differences in spatial sampling by the retina and the cortex (e.g. see Wilson, Levi, Maffei, Rovamo & DeValois, 1990). This knowledge led us to wonder whether the illusion was somehow related to differences in spatial sampling across the visual field. To test this idea, several experiments were performed. First, we observed the animation sequence from different viewing distances, to vary the angular subtense of the stimuli. At very close distances producing large retinal images, the illusion was still experienced in the periphery but not in the fovea. At twenty times this viewing distance, the illusion was not experienced in the periphery because the moving bar and the contours of the grating were unresolvable; nor did these small images produce an illusion with foveal viewing, even though they were visible. Indeed, so long as the elements of a foveally viewed display were resolvable—regardless of image size—the direction of motion appeared veridical. This pattern of results makes it unlikely that spatial sampling alone causes the illusion. In this regard, it is noteworthy that the curve summarizing illusion strength with eccentricity (Fig. 2) does not resemble the human cortical magnification curve (Cowey & Rolls, 1974).

Next, we tried viewing the animation sequence foveally with 10 D of blur, thus eliminating the higher spatial frequencies to which the periphery is insensitive. This manuever did not create the illusion in the fovea, indicating that high spatial frequencies are not essential for veridical perception. (With this degree of blur, neither the grating nor bar were resolvable in the periphery.) Are low spatial frequencies essential for the illusion? To answer this question, we created animation sequences in which the moving bar and background grating were either high-pass filtered or low-pass filtered, in both instances with a cut-off frequency of 1.43 c/deg. (The fundamental frequency of the square-wave

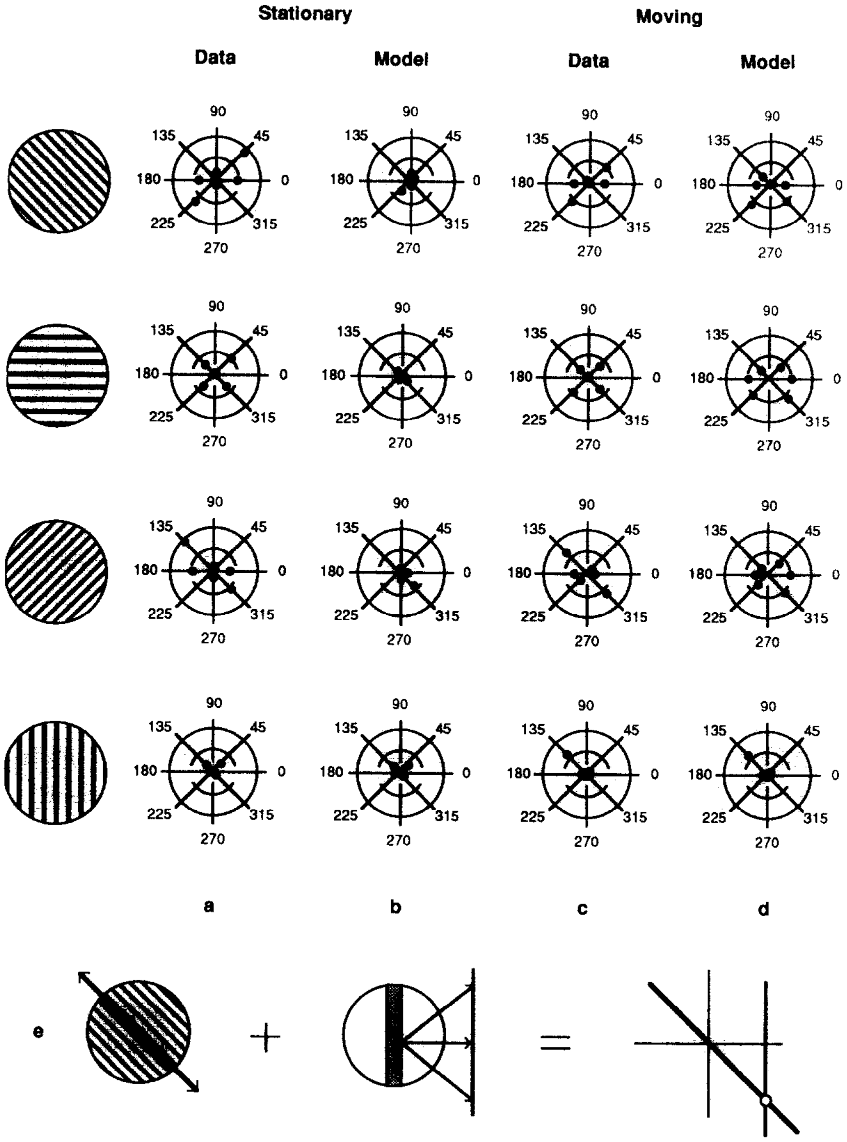

FIGURE 3. Polar plots of eight different directions of bar motion for each of four different background grating orientations (indicated by the four drawings at the far left of the figure). The values around the circumference of each graph specify the actual direction of motion of a vertical bar. (a) Each data point plots the angular difference between actual direction of bar motion and perceived direction of motion. Distance from the origin specifies the magnitude of illusion (i.e. the angular difference between actual and perceived). The inner circle denotes an illusion of 45 deg and the outer circle 90 deg. The four plots correspond to the four different background grating orientations (vertical, horizontal and the two obliques). (b) For each data point distance from the origin plots the difference between perceived direction of motion and the direction predicted based on the intersection of constraint lines associated with the given bar motion and grating orientation. (This analysis treats a stationary grating as one that moves in a direction parallel to its contours.) (c) Same as in (a) for the case where the background grating moves in a direction perpendicular to its contours. (d) Difference between perceived direction of motion and the direction predicted based on the intersection of constraint lines associated with a given bar motion and grating motion. Under some conditions the intersection of constraint lines predicts illusory motion opposite to real motion. Under such conditions observers reported either the predicted illusory motion (75%) or the veridical motion (25%). Averaged data of these two opposite motion directions leads to meaningless values and are therefore omitted from the plots. (e) Schematic representation of the intersection of constraints model for the case where a vertical bar moves over a grating oriented 45 deg anticlockwise. The single line over the grating indicates the two possible directions in which that grating could be moving behind an aperture. The single line next to the vertical bar delimits the range of possible directions of motions for a vertical bar moving rightward behind an aperture. The intersection of these two constraint lines is shown by the open circle in the far right of this diagram.

background grating was 1.36 c/deg.) With foveal viewing, both displays yielded veridical motion perception. With peripheral viewing, the illusion was experienced with the low-pass filtered sequence but *not* with the high-pass version even though the bar and grating were still visible. Evidently, the illusion depends on the presence of low spatial frequency information imaged in the periphery.

POSSIBLE EXPLANATIONS

Is the illusion novel?

Given the compelling nature of this illusion, we were rather surprised to discover that it has not been described previously in the literature. There are, of course, a host of visual illusions involving motion, but none encompass the phenomenon studied here. For instance, this illusion is not a version of reverse apparent motion (Braddick, 1980; Shiorir & Cavanagh, 1990; Anstis & Rogers, 1975), wherein a two-flash sequence produces motion in a direction opposite to the physical displacement. Reverse motion occurs when the brief interval between two successive motion frames have a particular luminance relative to the frames themselves, it is always in the direction opposite the physical displacement of motion elements, and it *is* readily experienced with foveal viewing.

The misdirected motion described here is not an instance of the illusion described by Henning and Derrington (1988), wherein a briefly presented grating moving, say, leftward appears to move rightward when the motion is viewed against another grating lower in spatial frequency. That illusion only occurs with presentation durations less than 200 msec, and it is seen foveally.

Does the illusion stem from the aperture problem?

We have considered the present illusion within the context of the intersection of constraints model developed to account for coherent motion perceived upon viewing component patterns drifting in different directions (Adelson & Movshon, 1982). On this model, the direction of motion of a contour viewed through an aperture is ambiguous, and the constraint line defines the family of possible directions of motion. The intersection of two constraint lines (one for each of two moving patterns) defines a unique direction in which the composite of the two patterns would move.

Now, one could construe a *stationary* background grating as one *moving* behind an aperture in a direction *parallel* to the orientation of the grating's contours, thus producing a constraint line for that "moving" grating. It is also possible to define a constraint line for a bar moving behind an aperture in a given direction and, then, to derive the intersection of the two constraint lines [Fig. 3(e)]. Accordingly, we derived the intersection of the constraint lines for the grating's motion and for the bar's motion for each condition shown in Fig. 3(a) and compared the direction of motion defined by that intersection with the bar's perceived direction of motion. As shown in Fig. 3(b), the intersection of constraints model provides a reasonably good prediction of the direction of the illusion measured 15 deg peripherally. It was, of course, impossible to judge whether the moving bar and grating cohered (i.e. comprised a single figure moving in a single direction).

To test the generality of the intersection of constraints analysis for the present illusion, we repeated the previous experiment under conditions where both bar *and* background grating moved. The grating drifted in a direction perpendicular to its contours, at a rate of 2 deg/sec. The bar motion was the same as that used before. As shown in Fig. 3(c), the illusion was essentially the same as with a stationary background grating [Fig. 3(a)]. Now, however, the intersection of constraints model poorly predicted the bar's perceived direction of motion [Fig. 3(d)]. Nor, for that matter, did the moving grating and moving bar appear to cohere. We therefore reject the idea that the present illusion results from the aperture problem.

Apparent motion from Hermann grid ghosts?

A number of observers spontaneously noted that the bar, when moving in the illusory direction under peripheral viewing, seemed to contain a fuzzy gray spot that traveled within its moving boundaries. This observation led us to wonder whether the stimulus conditions yielding the illusion were generating phantom spots of the sort associated with the familiar Hermann grid. The conventional explanation of the Hermann grid (e.g. Jung & Spillman, 1970) attributes the illusory spots to center/surround antagonism. As schematized in Fig. 4(a), the response of a neuron with a concentric receptive field will change depending on whether or not the receptive field is registering an intersection (compare the response at positions P_1 and P_2). Figure 4(b) illustrates how this conceptualization could be extended to the case of the illusory motion. At every instance in time, the vertical bar changes the response of the neuron, creating an illusory gray spot. Now, as the bar moves downward to the right over this grating (depicted at times T_1 and T_2), the gray "Hermann grid" spots are situated increasingly upward to the right. Perhaps, then, the illusory direction of motion results from apparent motion of the illusory spots created by this Hermann grid-like stimulus. This explanation could also readily account for the variation in illusion strength with eccentricity, since it is well established that receptive field sizes (and, for that matter, the vividness of the Hermann grid illusion) vary with eccentricity.

To test this "Hermann grid" hypothesis, we determined whether the motion illusion is experienced under scotopic viewing conditions. The Hermann grid illusion disappears at scotopic levels (Patel, 1966; Wist, 1976; Troscianko, 1982), and so too should the motion illusion if the idea depicted in Fig. 4(b) is correct.

Four observers (two naive) were tested individually in the following manner. The video screen was dimmed to its lowest value using the contrast and intensity controls, and the observer monocularly viewed the screen through a pair of polarizing filters that could be rotated to dim the display even further. (The observer wore a patch over the untested eye.) First, the observer was dark adapted for 20 min and then situated in front of the filtered display and given a 2 alternative forced-choice color discrimination task. This involved viewing a pair of Hermann grid displays presented side-by-side on the video screen. One grid was colored and the other was some value of gray; over a series of 14 trials, the observer guessed which display—left vs right—was colored. Performance on this task never exceeded chance level, nor did observers describe seeing Hermann grid spots even though the grid pattern itself was visible.

Next, the observer viewed a prototypical illusion display (i.e. a diagonally oriented grating with a vertical bar moving perpendicular to the contours of the grating). The observer was instructed to slowly rotate one of the polarizing filters to a position where the

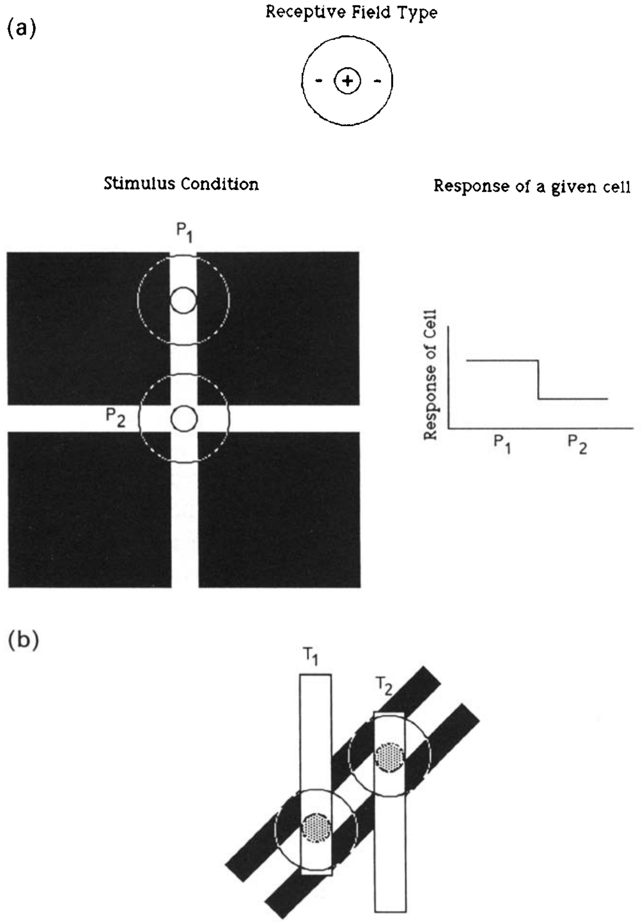

FIGURE 4. Possible explanation of illusion based on Hermann grid. (a) Conventional explanation of Hermann grid spot, where receptive field at position P_1 yields stronger response than receptive field at position P_2. (b) Schematic depicting a vertical bar moving down and to the right at time T_1 and time T_2. Note how the putative Hermann grid spot within the bar moves up and to the right, the direction of illusory motion with peripheral viewing.

moving bar was visible with peripheral viewing but was invisible with foveal viewing; the resulting luminance values ranged from 0.004–0.024 ftL among the four observers. The observer was now tested on a series of 40 trials at this luminance value. On each trial the observer moved the cursor to the point around the perimeter of a centrally viewed circle to match the apparent direction of motion of the peripherally viewed bar (same procedure as that used in Expt 2). The background grating's orientation and bar's direction of motion were factorially varied to yield 20 trials where the illusion was ordinarily experienced and 20 where motion perception was veridical. Under the first set of conditions (i.e. those normally yielding the illusion), the illusion was experienced in 72% of trials; under the second set (i.e. those normally yielding no illusion) motion was accurately perceived.

Finally, the color discrimination test was re-administered at the same light level utilized for the illusion test. Again, observers performed at chance level, confirming that our tests were carried out at scotopic levels. These results provide no support for the Hermann grid hypothesis of illusory motion. It is noteworthy that observers did not describe seeing a gray spot within the moving bar under scotopic conditions, even though the motion illusion itself was experienced. From this we conclude that the illusory gray spot seen under photopic conditions is ancillary to the motion illusion, not a critical determinant of it.

Motion energy in the illusory direction

Having rejected the explanations advanced above, we next tried to reconceptualize the stimulus conditions yielding the motion illusion by examining the local motion vectors created when a square (whose direction is never misperceived) or a bar (whose direction may be misperceived) moves across a grating. Consider a square moving across a grating from location 1 to 2 [upper portion of Fig. 5(a)]. The local motion signal from the vertical edges of the square is horizontal [vector $x1$, lower portion of Fig. 5(a)]. Similarly, the local motion created by the top and bottom edges is vertical (vector $y1$). The resultant sum, vector $s1$, describes the motion of the square and also describes its perceived motion path in foveal and peripheral vision. In this animation sequence, there are two additional sets of motion signals produced by the changing locations of the intersections of the square's edges with the contours of the grating. Shown as vectors $m1$ and $n1$, these signals are 90 deg from $s1$ and 180 deg from each other. Vector $m1$ specifies motion downward parallel to the grating, and vector $n1$ motion upward in the opposite direction. These vectors, being equal and opposite, cancel. Consider next a vertical bar moving from position 1 to 2 [Fig. 5(b)]. Vectors $x2$ and $y2$ describe the motion signals from the bar's vertical and horizontal edges; because the extent of movement in both directions is equal, the two vectors are equal in length. The sum of these vectors, $s2$, describes the path of the bar, and this matches its perceived path in foveal vision. But in peripheral vision, the illusory direction of this bar matches the direction of vector $n2$, the motion signal created over time by the change in position of the intersections of the bar's vertical edge with the grating. The opposite vector $m2$ is much shorter than $n2$, because the bar's small width limits the spatial extent of travel of a motion signal created by the intersections of the top and bottom edges with the grating. As a result, $m2$ and $n2$ do not cancel, creating a net motion signal in the direction of $n2$ (i.e. the direction of the illusion). For a horizontal bar [Fig. 5(c)] $m3$, which specifies motion in the illusory direction, greatly exceeds $n3$. (This same analysis may be applied to the condition where bar and grating move.)

The preceding analysis reveals that the display studied here contains motion energy in the direction of illusory motion. Several recent models of motion perception posit the existence of spatio-temporal filters that extract motion energy locally (Adelson & Bergen, 1985; van Santen & Sperling, 1984; Watson & Ahumada, 1985). Such filters would register motion in the illusory direction. Now, this conceptualization raises an intriguing question: if the motion energy defined by vector $n2$ [the condition in Fig. 5(b)] or by vector $m3$ [the condition in Fig. 5(c)] underlies the illusion in the periphery, why is

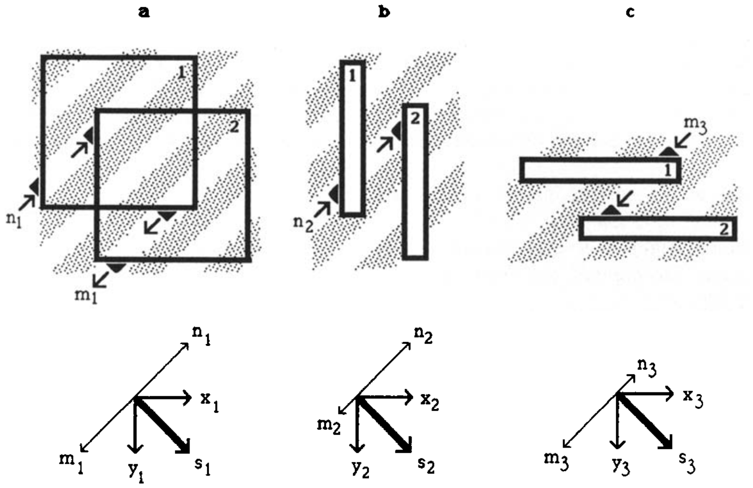

FIGURE 5. Schematic showing local motion signals produced when a square (a), a vertical bar (b) or a horizontal bar (c) moves across a grating whose contours are oriented 45 deg clockwise from vertical. The upper portion of the figure shows two frames from the motion sequence (the figures numbered 1 and 2), and the bottom portion shows the resulting motion vectors. The length of a vector is proportional to the spatial extent of local motion from frame 1 to frame 2. The locations of the intersections of bar and grating creating motion vector $m2$ are too close together to show on the upper portion of (b); this is why vector $m2$ is so short in the lower portion of (b). The same is true for vector $n3$ in (c). See text for further details.

that motion energy ineffective when viewing is foveal? Recall we were unable to produce illusory motion in the fovea either by scaling the size of the object or by spatially filtering it. The inability to generate a foveal illusion implies that vector $s2$ [the condition in Fig. 5(b)] or vector $s3$ [the condition in Fig. 5(c)] determine perceived direction in the fovea. Moreover, the graded increase in illusion magnitude shown in Fig. 2 implies that the relative contributions of $s2$ and $n2$ (or $s3$ and $m3$) vary systematically with retinal eccentricity. In the computation of global motion, then, the local motion energies (e.g. $s2$ and $n2$) may be weighted differently with eccentricity, with $n2$'s contribution amplified in the periphery.

Recently, several authors (Chubb & Sperling, 1988; Wilson, 1991) have proposed the existence of two different motion mechanisms, one that performs a Fourier-type analysis (i.e. one that derives motion energy from linear spatio-temporal filters) and another that extracts motion from a signal that has undergone a non-linear transformation (e.g. full-wave rectification). Both mechanisms are operative at any given region of the visual field, but their relative contributions to the resulting motion percept may vary with eccentricity. The illusory motion studied here may reflect differential activity in these putative mechanisms. This explanation remains speculative, however, since these dual process models have not been sufficiently developed to allow us to derive predictions concerning variations in illusion strength with eccentricity (recall Fig. 2).

CONCLUSION

Whatever its neural basis, this striking illusion may have practical perceptual consequences. In everyday environments, objects in the peripheral visual field often move relative to a textured background, and according to our observations the resulting motion signals can be misleading. In certain situations, such as navigating a vehicle or dodging an approaching object, the misperception of direction of motion could produce serious errors in the perceiver's visuo-motor response.

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Acknowledgements—This work was supported in part by NIH grant EY 07760. We thank Amy Koerner and Ellen Roche for help in data collection and analysis.