Local and global segmentation of rotating shapes viewed through multiple slits

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Rotating outline squares and circles were viewed through a sunburst pattern of stationary radial slits. At slow rotation rates the (dotted) square was perceived globally as a single rotating shape, and at higher rates, as a set of independent local dots moving in and out radially. An eccentrically rotating circle was seen as a dotted circle; the dots comprising the circle actually moved in and out along straight radial paths, but observers could never see this. Instead, they saw the dots as running around the rim of the circle. The common motions were rejected, perhaps by subtracting the mean motion of all points from each point. Only relative motion could be seen, and absolute dot motions were not available to consciousness. Thus the visual motion system parsed patterns of absolute motion vectors into patterns of relative motion vectors.

Keywords: 2D motion, aperture problem, segmentation

Introduction

The *sensation* of motion is produced by stimulation of neural motion sensors at different retinal positions (van Santen & Sperling, 1985). However, the *perception* of motion requires a parsing and segmentation of the local motion signals. This work describes the perception of some outline figures rotating behind a sunburst pattern of 24 thin, stationary radial slits. The slits break the figures up into moving dots but the patterns of dots are ambiguous in various ways. Results reveal competing mental tendencies to organize motions globally, especially at low speeds, or locally, especially at higher speeds. Moreover, the absolute motion paths of the dots are often unavailable to consciousness because they are preempted by perceptual parsing into patterns of relative motion.

Some earlier studies on rotating patterns used no apertures or occluders at all; some have used large square apertures; and some have used translation behind stationary slits. Among studies without apertures, Farrell and Shepard (1981) examined apparent rotational motion in polygonal shapes ranging in rotational symmetry from random to self-identical under 180-deg rotation. Observers adjusted the rate of alternation between two computer-displayed orientations of a polygon to determine the critical time at which rigid rotation broke down into nonrigid deformation. For asymmetric polygons, this critical time increased linearly with orientational disparity, consistent with Korte's third law of motion. For nearly symmetric polygons, however, the critical time increased markedly as the disparities approached 180 deg, because of the availability of a shorter, nonrigid rotation in the opposite direction. The results demonstrate the existence of competing mental tendencies to preserve the rigid structure of an object and to traverse a minimum transformational path. Weiss and Adelson (2000) examined rotating ellipses. They found that narrow ellipses appeared to rotate, whereas fat ellipses appeared to deform in a gelatinous way. Adding four moving dots just outside the perimeter of the ellipse controlled the perceived motion: If the dots rotated, the ellipse also appeared to rotate, whereas if the dots moved in and out radially the ellipse appeared to deform. The results failed to fit computational models that pool constraints over a local area only, models that propagate information along contours, or models that indiscriminately propagate information across space. The authors proposed that the visual system splits the visual display into layers and then applies smoothness motion constraints to each layer separately. For instance, when an ellipse rotated in front of a pattern of drifting random dots, the ellipse and the dots are first split apart by perceptual scission and then their motions are analyzed separately. Sparrow and Stine (1998) studied the perception of the shadows of rotating eight-vertex geometric forms.

Shiffrar and her coworkers moved lines and figures around behind *apertures*. They found that observers consistently perceived the fixed center of rotation for an unmarked line viewed through an aperture as located on the line, regardless of its actual location. Accuracy greatly improved with visible line endings. This finding was extended to explain why a square appeared nonrigid when it rotated behind four occluding portholes, each porthole being about half as wide as the square. The square appeared to expand when its corners were visible and to shrink when they were hidden, and only parts of the straight sides were visible. Observers seemed unable to apply an object rigidity constraint across apertures (Shiffrar & Pavel, 1991; Meyer & Dougherty, 1990).

In other experiments the square moved around a circular path without rotating, like the sponge in the hand of a window cleaner. When the corners were hidden, and only straight sides were visible through the four portholes, each straight side was ambiguous because of the aperture prob-

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lem, and again observers were unable to integrate across the four apertures to see a rigid square. Strangely, integration was much better when the sides were not clearly seen, for instance, when they were low in contrast or viewed peripherally (Lorenceau & Shiffrar, 1992; Shiffrar & Lorenceau, 1996).

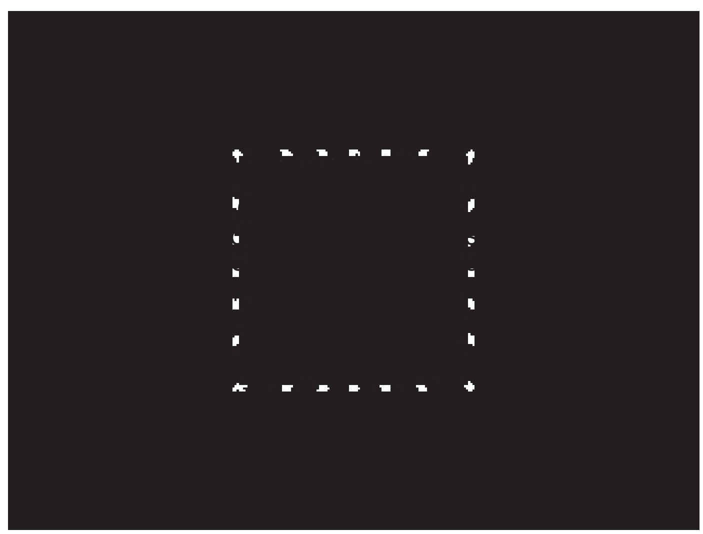
There have been many studies of shapes that translate rapidly behind a *single* slit (e.g., Casco & Morgan, 1984). Morgan, Findlay, and Watt (1982) have reviewed this literature. Observers often report seeing the whole shape, compressed along its axis of movement but surprisingly much broader than the narrow viewing slit. Opinion is still divided on whether this is a mundane case of retinal painting caused by eye movements (Anstis & Atkinson, 1967) or whether the visual system is able to integrate successive visual snapshots as they arrive, a slitful at a time (Nishida, 2004).

In this study, outlined shapes always rotated behind stationary, *multiple, thin slits*. Bruno and Bertamini (1990) studied the perception of surface contours specified by occlusion events that varied in density, velocity, and type of motion (rotation or translation). Their observers viewed either a square rotating behind stationary slits, as we did, or else slits rotating in front of a stationary square. Observers had to report whether the square had straight or curved edges. Performance increased with rotation speed and with number of visible points, that is, the number of slits. Puzzlingly, they found that performance was far better for rotating slits than for rotating squares; the reasons for this were not clear. Nishida (2004) displayed moving targets behind a virtual "picket fence" that obscured the scene except for thin slits between the pickets. Observers could read wide alphanumeric characters that moved behind these narrow slits, even during strict fixation, clearly relying upon spatiotemporal integration within the motion system. Using an adaptation of the reverse-correlation technique, he showed that the spatial frequencies used for the letter- recognition task were higher than the limit imposed by spatial sampling through the slits, and thus were only available by temporal information (Burr & Ross, 2004). This provides clear evidence against the notion of separate analysis of motion and pattern. Instead, motion mechanisms integrate spatial pattern information along the trajectory of pattern movement to obtain clear perception of moving patterns. The pattern integration mechanism is probably a direction-selective filtering by V1 simple cells, but the integration of the local pattern information into a global figure may be guided by a higher order motion mechanism such as MT pattern cells.

For completeness, we refer to an interesting study by Bruno and Gerbino (1991), whose stimuli were somewhat like ours, although they studied quite different perceptual effects. In their display, an invisible white triangle on a white surround occluded a set of black lines radiating from a point behind the center of the triangle. This illusory triangle occluded the lines rather as Kanisza's illusory square occludes four pacmen. When the line pattern rotated behind the stationary triangle, the triangle was easily perceived. However, if the lines kept still and the triangle rotated in front of them, observers reported only an amoeboid shape instead of a regular, rigid triangle. The authors attribute this "background superiority effect" to perceptual extraction of local kinematic information.

Experiment 1

Observers viewed a thin luminous outline square rotating behind a set of 12, 24, or 48 thin stationary slits that radiated from a common center, and were cut in a black virtual occluder. The stimulus is shown in Movie 1. At any given instant, the radial slits split the square up into a dotted square. But any given dot moved back and forth over time along a straight line behind its slit, moving toward and away from the center of the radial slit pattern. Observers were asked to report on the subjective appearance of this display by hitting one of five designated computer keys: Did the motion rotate "around and around" (key 1), go "in and out" in a pattern of radial expansion and contraction (key 5), or "something in between" (keys 2 to 4)? All key presses were recorded for later analysis. The idea was that a percept of a unitary rotating square (key 1) indicated that dots within a single movie frame cohered together spatially, while a percept of dots moving in and out (key 5) indicated that temporal cues from a given dot across successive frames predominated over spatial cues.

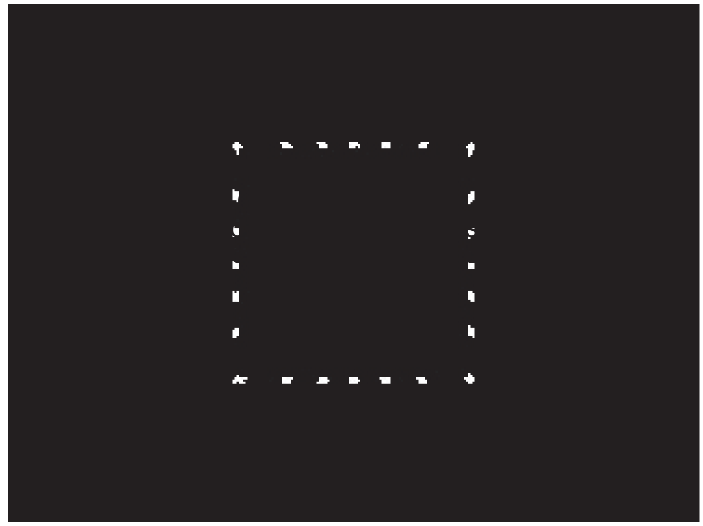


Movie 1.

The square rotated at an angular rate chosen randomly on a trial-by-trial basis from a 12-fold range of speeds that ranged from 50°/s to 600°/s in steps of 50°/s. These angles refer to rotation rate, not to visual degrees subtended at the eye, so that 360°/s is equal to 1 rev/s. In other words, the rates ranged from 0.14 to 1.67 rev/s. Ten trials were run at each rotation rate, and for each set of slits (12, 24, or 48), in random order.

Samples of the movie running at slow and fast speeds are shown in Movie 1 and in Movie 2. (Speeds, line widths, etc., shown on your computer screen may not exactly match those used in the experiment. Actual stimuli used were rather more convincing than the versions shown here).

The side of the rotating square subtended 5.8° of visual angle and was viewed from a distance of 57 cm in a dimly lit room. The display was programmed in Macromedia Director running under Mac OS X and was displayed on a Sony Trinitron G400 Multiscan monitor screen at a screen resolution of 1280 x 960 pixels at 75 Hz, controlled by a G4 Macintosh computer.



Movie 2.

Results

Results are shown in Figure 1 (mean of 4 Ss x 10 trials). Figure 1 shows that at slow rates the square tended to be perceived as rotating. As the speed increased, the perception increased monotonically toward expansion/contraction. In addition, a closer spacing between slits encouraged the percept of a single rotating square, because the data for 12 slits lie at the top of the graph (slits far apart, perception of dots moving in and out), while the data for 48 slits lie at the bottom of the graph (slits close together, perception of a rotating square).

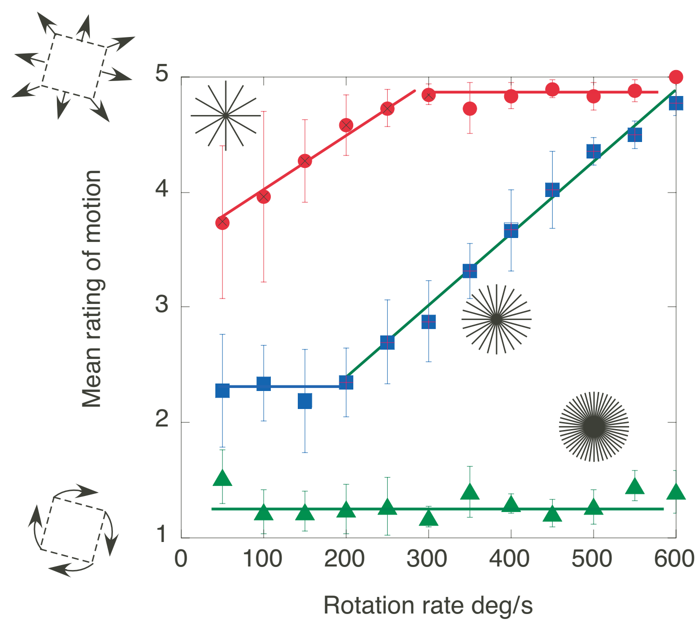


Figure 1. Results of Experiment 1 (mean of 4 observers). An outlined square rotated behind 12, 24, or 48 fixed radial slits. Both increasing the number of slits and slowing the rotation rate increased the probability of seeing rotation (y→ 1). Thus, seen through 48 slits (green triangles), the square nearly always appeared to rotate. With 12 slits (red circles) or 24 slits (blue squares), at slower rotation rates observers still tended to report a single rotating square. At faster rates they reported many dots moving in and out independently.

Discussion

These results show that for slow speeds and/or closely spaced slits, observers tended to organize the motion into the global percept of a single rotating square, even though all dots actually followed radial not tangential (rotary) paths. Thus the perceptual spatial links between simultaneous dots predominated over temporal links between dots at successive times. At higher speeds, however, this global organization gradually broke down and gave way to a local perceptual organization in which each individual dot was veridically seen as moving in and out radially, without regard to its fellows. This perceptual changeover from a slow square to rapid radial motion shows that the shorter the spatial interval, the more spatial coherence was seen – a single rotating square – and the shorter the temporal intervals, the more temporal coherence was seen – individual dots moving radially. In other words, moving the slits further apart required a slowdown in speed to maintain the cohesion of the square. This gives us an opportunity to evaluate an equivalence function between space and time. In Figure 1 the horizontal portions of the curves where responses saturated are uninformative, but the sloping portions of the two upper curves are virtually parallel and can be exactly aligned, with a mean misalignment of less than 0.1°, by shifting the 12-slit data curve horizontally through a distance of 350° on the *x*-axis. This brings it into exact register with the 24-slit data curve. This implies that *halving* the angular separation between slits from 30° to 15° (i.e., doubling the number of slits from 12 to 24), which increases the probability of seeing rotation, can be nulled out by increasing the rotation rate by 350°/s – almost exactly *1 rev/s*. Clearly, this equivalence function holds over only a limited range of conditions.

Experiment 2

To investigate further the global organization at low speeds, we changed the stimulus from a concentrically rotating square to an eccentrically rotating circle that rotated behind 24 stationary radial slits at a rate of 120°/s (1 rotation every 3 s). This was a slow speed that had nearly always yielded the percept of a rotating square in Experiment 1. A sample stimulus is shown in Movie 3. The center of rotation always lay between the geometrical center and the periphery of the circle. When observers were asked to describe what they saw, they were able to specify three different motion components, namely a dotted circle that rotated eccentrically clockwise, with the dots running around the edge of the circle in two different ways. A wave of compression and rarefaction appeared to move clockwise around the rim of the circle, and the most widely spaced (rarefied) dots appeared to move rapidly counterclockwise around the rim of the circle. Naive observers did not notice or deduce the presence of the radial slits.

The stimulus circle rotated eccentrically, and its eccentric center of rotation always lay between the center and the periphery of the circle. Specifically, it was positioned at a distance of .025, 0.4, 0.62, 0.75, or 0.89 of a radius out from the center. (A distance of zero radii would correspond to a circle that rotated about its own center, and a distance of one radius to a circle that rotated about a point on its own periphery.) The computer randomly selected one of these eccentricities on a trial-by-trial basis.

Next to this stimulus circle was a matching circle, also made of 24 dots. This rotated about its own center (not eccentrically) at a rate that the observer controlled by means of the computer mouse. Observers were given two different tasks on different blocks of trials; they were asked to adjust the rotation of the matching dotted circle either to match subjectively the clockwise rotation of the wave of compressed dots as they traveled around the stimulus circle or to match the counterclockwise rotation of the widely spaced dots, whose position was diametrically opposite the wave of compression. (They were not asked to match the eccentric rotation of the stimulus circle as a whole.) So the observer moved the mouse back and forth to adjust the rotation rate of the matching circle until satisfied that it matched the perceived rotation of either the wave of compressed dots or of the individual rarefied dots. He or she then clicked the mouse, the reading was stored for later analysis, and a new eccentricity was randomly presented for the next trial.

Results

Results in Figure 2 show that the observers matched, with very small *SE*s, the rotation of the stimulus dots *with respect to the moving center of the circle* in which they were embedded. Afterward, observers were asked to draw a sketch of how the stimulus might look if each moving dot

Movie 3.

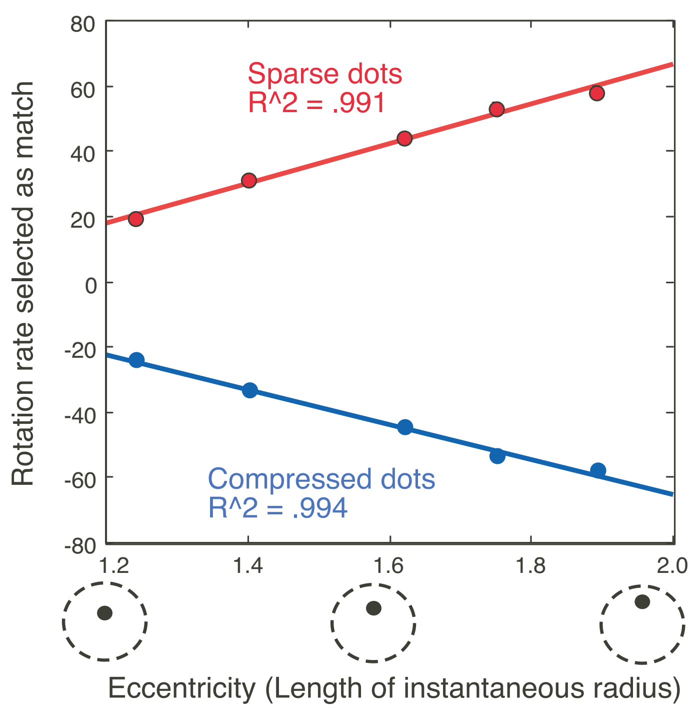


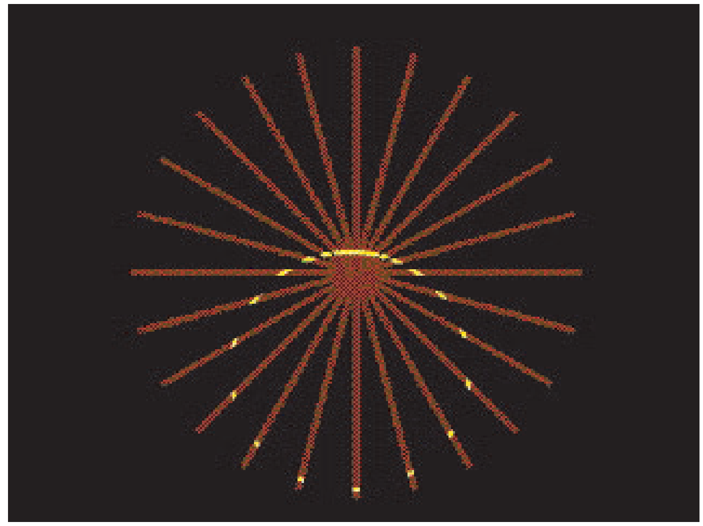
Figure 2. An outline circle rotated at 120°/s behind the same 24 fixed slits as in Figure1. The eccentricity was varied, with the long radius of rotation from the eccentric point being 1.25, 1.4, 1.62, 1.78, or 1.89 radii of the circle. Observers were quite unable to discern that each dot moved back and forth along a straight slit. Instead, they perceived them as running around the rim of the moving circle. The upper curve (red circles) shows perceived counterclockwise rotation rate of the most widely spaced dots, and the lower curve (blue squares) shows perceived clockwise rotation rate of the most closely spaced dots (wave of compression). All *SE*s were smaller than the plotting symbols.

were to leave an inky trail across the monitor screen. In each case they drew a complicated wiggly trajectory that bore no relationship at all to the true linear dot paths. We explain this with a simple model, illustrated below in Figure 3, in which observers subtract out the absolute motion of the whole circle and perceive only the motion of the individual dots relative to that circle.

The experimenter then lightened the background seen through the slits, making the slits visible and revealing the true state of affairs. This is shown in Movie 4. Every observer expressed surprise and had previously had little or no idea of the existence of the slits – nor of the fact that these slits constrained each dot to travel back and forth along a straight line. However, when the slits were visible, as in Movie 4, the naive subjects still saw the intersections as moving in circular patterns as opposed to radial motions. We return to this when we discuss moving plaids later on.

Figure 3 compares diagrammatically the actual and perceived trajectories of the dots. (For clarity, the number of radial slits has been reduced from 24 to 12 in Figure 3.)

Figure 3a shows two separate time frames of the stimulus, with the stimulus circle rotated through 30° between the two frames. The intersections of the eccentrically moving circle with the stationary slits are shown as red dots at Time 1 and as green dots at Time 2. In the actual stimulus (Figure 3a), all dots move to the right, converging toward the eccentric center of rotation in the left half of the figure and diverging away from it in the right half (black arrows). However, observers never saw the dots as moving in straight lines, but always as running around the edge of the circle. The reason why is diagrammed in Figure 3b, in which the two circles of dots have been hypothetically shifted into coincidence, as though the observers were either ignoring (canceling out) the circle's movement or were misperceiving the circle as if it were apparently rotating about its own geometric center (instead of about the actual eccentric center of rotation). In Figure 3b the dots move in the directions (black arrows) that match observers' subjective reports.



Movie 4.

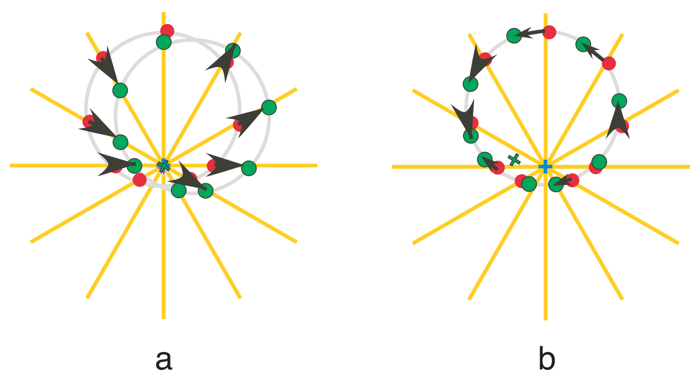


Figure 3. a. Actual intersections of the eccentrically rotating circle with the stationary slits are shown as red dots at Time 1 and as green dots at Time 2. All dots are constrained to move back and forth along straight lines behind the slits. However, observers never perceived linear motions. What they perceived is shown in b. The clockwise shift of the whole circle between T1 and T2 was perceptually subtracted out; this is indicated by sliding the circles into superimposition. Now the dots are perceived as running around the rim of the circle, counterclockwise where they are widely spaced (near 12 o'clock) and counterclockwise where they are bunched up (near 6 o'clock).

Relationship to other motion phenomena

The situation shown in Figure 3 is similar to Johansson's observation that when a friend waves to you from a moving train, his hand describes an extended sine wave in space, but that is not what you see. Instead, you partial out the two motions and see a train moving horizontally plus your friend's hand moving up and down with respect to the train's window (Johansson 1975: Johansson, von Hofsten, & Jansson 1980). You apply a "common mode rejection" operation, taking the horizontal component that is common to the train and to your friend's hand and perceiving hand and train as moving along together. This leaves a residual up-and-down sinusoidal motion component of your friend's hand, which you assign to the hand. It is easy and normal to parse the hand motion with respect to the train, but difficult to parse it with respect to the ground. Similarly, you extract the common motion of the eccentric circle and of the dots that define it, and see a dotted circle rotating eccentrically. This leaves residual motions of the dots, which you parse as running around the rim of the circle. Common motion can be removed by subtracting from every point the mean motion of all the points; this converts motion relative to the ground into motion relative to the wheel, or to the train. We noted that not only can the dots be grouped with the circle – they cannot be ungrouped from it! Perceiving the dots as being attached to the circle is obligatory, and observers are quite unable to perceive, except by means of careful attentive scrutiny, that the path of every dot across the monitor screen is not a circle, nor a waved wave, but a strictly straight line. We conclude that they organize the local motion signals into a *global* percept, based on common mode rejection and yielding the simplest and most probable hypothesis of what physical object is most likely to produce the complicated pattern of motion signals that arrives at their retina.

Ternus display

The rotating dotted square in Experiment 1 is ambiguous, not illusory. Taken all together, the group of dots really does comprise a rotating square. Taken individually, each dot really does move in and out along a straight line. Both percepts are veridical, and each accounts for all of the data. The display has much in common with the Ternus display (Ternus, 1926), in which three dots at positions a, b, c alternate over time with three dots at positions b', c', d. At rapid alternation rates, with short interstimulus intervals (ISIs), one sees a single dot jumping back and forth between position a, d, across two stationary dots at positions b, c (element motion). At slower rates, with longer ISIs, one sees all three dots jumping back and forth together (group motion). Compare this with the dotted square, which at rapid alternation rates gives individual element dots moving back and forth, while at slow rates it gives group motion of the whole square. In both cases, a slow alternation rate weakens the temporal link between successive appearances of each local dot and encourages the spatial grouping of the three Ternus dots into a trio, or of our multiple dots into a square.

Plaids

Our finding that speed influences the perceived coherence is in line with what we know from the plaid literature (Adelson & Movshon, 1982; Movshon, Adelson, Gizzi, & Newsome 1983; Stoner & Albright, 1994; Wilson, 1994). We can think of our display as a form of plaid, where the stationary slits form one component, the rotating outline square forms another component, and the intersections between the square and the slits, which appear as dots on the screen, are the pattern. (It is true that the stationary slits were invisible, but we mentioned earlier that increasing the slit luminance to make them visible did not alter the perception of rotating square versus dots moving in and out.) The visual system needs to decide whether these intersection motions are spurious and hence should be discarded. We found in Figure 1 that at high speeds with widely spaced slits, one perceives local in-and-out motions of the dots – that is, pattern motion – and at low speeds or with closely spaced slits one perceives global rotation of a square – that is, motion of a component. In other words, short temporal intervals and long spatial intervals favored the pattern motion of individual dots, because each dot was more likely to link up with a corresponding dot across successive movie frames. Long temporal intervals and short spatial intervals favored component motion of the rotating square, because all dots within a movie frame were more likely to link up spatially to form a square.

The coherence of plaids is affected both by the absolute and by the relative speeds of the components and the pattern – when the component motions are far slower than the pattern motion, the stimulus will not cohere (Wilson, 1994). Here, speeding up our whole display increases the absolute speeds, of course, but it does not change the ratio of pattern speed to the component speeds. The tangential velocity of the rotating square component is four or five times greater than the radial velocity of the individual pattern dots as these run back and forth within a slit. This ratio of pattern to component velocities remains constant at all display rates, so it cannot determine the percepts. It may be, however, that the visual system has a range of preferred absolute speeds, and whichever item – components or patterns – falls within that speed range is more likely to be perceived. At all events, Welch and Bowne (1990) pointed out that an observer can retrieve information about the motion of either the plaid's components, or of the plaid itself, but not both.

Chopsticks

In the chopstick illusion (Anstis, 1990, 2003), a vertical line and a horizontal line are superimposed to form a cross. Each line moves along a separate clockwise path without rotating, like a sponge in the hand of a window cleaner. The two lines move in counterphase, with one line being at 12 o'clock when the other is at 6 o'clock. The point of their central intersection, where the lines slide over each other, actually moves along a counterclockwise path but it is perceived as moving clockwise. The illusion is compelling; when this display was shown to a class of 230 naive students, 199 of them (86%) reported the intersection to be moving clockwise (Anstis, 2003). Possibly, the visual system refuses to parse the sliding intersection as an object, and instead, the clockwise motion of the tips of the lines propagates along each line and is blindly assigned to the intersection. When the lines are viewed through a stationary aperture that conceals the line tips, the intersection is now correctly seen as moving counterclockwise. In addition, it is seen as a rigid cross instead of as two sliding lines.

The chopstick illusion is related to a plaid stimulus, insofar as each chopstick resembles a component grating and the sliding intersection resembles a moving plaid. However, the chopstick effect is a true illusion, in that the perceived direction of rotation is opposite to the actual direction. It is not ambiguous, and it does not involve a partialling out of relative motion vectors. Thus the chopstick illusion is probably not closely related to our dotted-square or dotted-circle displays.

Conclusions

We conclude that our moving dotted square has points in common with the Ternus display and with moving plaids, whereas our moving dotted circle is logically descended from the parsing of absolute motion arrays into sets of relative motion vectors (Johansson, 1975, 1980).

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