Perception, 2000, volume 29, pages 843 – 851

DOI:10.1068/p2929

Form and movement in stereokinetic cycloids: motion lost and found

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Received 9 March 1998, in revised form 24 November 1999

Abstract. In exploring stereokinesis, we devised flat cycloidal display figures which, when rotated on a disc in the frontal plane, are perceived as illusory three-dimensional forms with movement in depth; the dominant percepts were of twisted loops with an internal writhing motion. These dominant forms could be convincingly represented by stereo pairs derived from the flat display; related forms, not seen in the illusion, could also be constructed, seeming to show a selectivity for preferred stereokinetic forms by the perceptual system. Models were made of the stereo forms; when rotated, they showed similar illusions and selectivity. We suggest that the illusions arise because some components of the real motion do not appear in the sensory field. The perceptual system accommodates for this by constructing percepts which are not necessarily veridical but do reconcile form and motion into a coherent unity. The results are discussed in relation to concepts of invariance and rigidity, and with regard to the creative response to sensory data by the perceptual system.

1 Introduction

Following earlier researches into the stereokinetic effect, in which flat displays rotated in the frontal plane are perceived as having three-dimensional structure (Musatti 1924, 1975; and many others), we published studies of the part played in the effect by motion along contours, which we chose to call 'lost motion' since it is a type of motion which, because it does not change retinal stimulation, is not sensed and therefore can be included in the percept only by inference (Wilson et al 1983, 1986; Robinson et al 1985). Since that time several theories have been developed to explain the illusions, largely in geometrical terms (Zanforlin and Vallortigara 1988; Beghi et al 1991a, 1991b; Profitt et al 1992; Caudek and Profitt 1993). These theories work well in that they have clearly specified the projection of the display at the eye, but there are some effects which they do not predict. Thus, Caudek and Profitt remark that even in some cases where the stimulus information should allow a geometrical derivation of depth, the psychological process cannot be characterised in these geometrical terms. They propose instead that the perceptual derivation of monocular depth from motion might be better described as a heuristic process of which the stereokinesis is symptomatic: "Assumptions inherent to the perceptual system augment the perception of depth from monocular motion".

We believe that 'lost motion' is one of these assumptions, and in our present work we have devised displays which exploit lost motion to produce illusions of 3-D structure and motion. The illusions so produced seem to us to further the view that higher functions, heuristic or constructional, play an important part in the perception of depth in the displays.

In previous work we were able to make a variety of displays which when rotated would produce illusions of familiar 3-D forms: cones, wobbling discs, spheres, bells, and so on (figure 1). However, effects were observed which, like those remarked on by Caudek and Profitt (1993), went beyond the simple geometry of the display; eg when the display of eccentric circles was perceived as a wobbling cone, we (and some of our subjects) saw an elastic membrane which appeared at the base of the cone, merging the

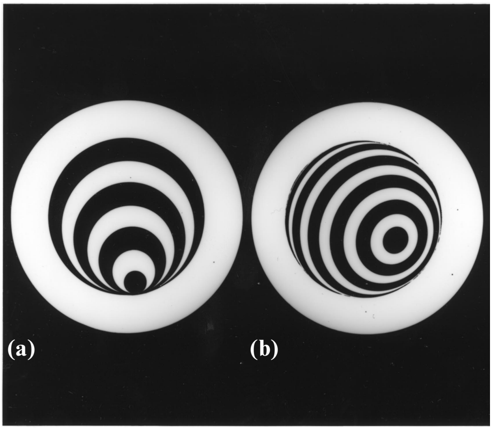

Figure 1. Stereokinetic displays: (a) stereokinetic banded cone, (b) stereokinetic banded sphere.

wobble of the cone to the firmness of the disc. Similarly, with prolonged inspection, the wobbling sphere appeared to be complete but partly occluded in the way that parts of a rolling eyeball are covered by the eyelids. Similar effects were observed by Vallortigara et al (1986) and Zanforlin and Vallortigara (1988).

To provoke interesting effects we needed figures in which lost motion varied systematically across the figure. We also wanted the displays to be unfamiliar, so that promising illusions would not be hidden by habitual percepts. If we could produce displays with new variations in lost motion, they might be susceptible to simple interpretations which the perceptual system could discover and build into new percepts. Such a percept, constructed by the system to 'explain' a sensory input with a substantial amount of unfamiliar but coherent lost motion, might well be far from veridical.

In the event, we were able to draw cycloid patterns which served our purpose, producing illusions not only of moving objects with depth but also, not so common in stereokinesis, of objects with movement in depth.

For displays, we made a set of computer drawings of the cycloid patterns, 1 to 6 lobes outward and 1 to 6 lobes inward (figure 2). The 1-lobe and 2-lobe outward figures are too simple, and were not used. The 3-lobe outward figure resembles a figure used by Braunstein and Andersen (1984): theirs was constructed from circular arcs but approximates to a cycloid.

2 Procedure

Our main procedure was to observe a flat display figure mounted on a disc which was rotating in the frontal plane. The illusory effects were robust, and tolerant of changes in visual angle, illumination, and speed of rotation.

We were interested in careful qualitative description, not in measurement. Since it was clear that the effect was both robust and complex, we did not use naïve subjects, but recorded our own observations. All the recorded observations were made monocularly in a well-lit room. The displays were 18 cm in diameter, placed 1.5 m from the observer, and were rotated mostly at 33 rev. min^{-1}.

We observed the effect in detail, working through the set of displays from 3 to 6 lobes, outward-turned, and then from 1 to 6 lobes inward-turned. When necessary we returned for further observations. We noticed two main effects: of well defined form with a strong appearance of depth, and of apparent movement within the curve, writhing through the confinement of the near-rigid form. These effects were clearly seen and described by both observers, and will be discussed in the next section. Many other aspects were seen, but they were unstable and did not persist.

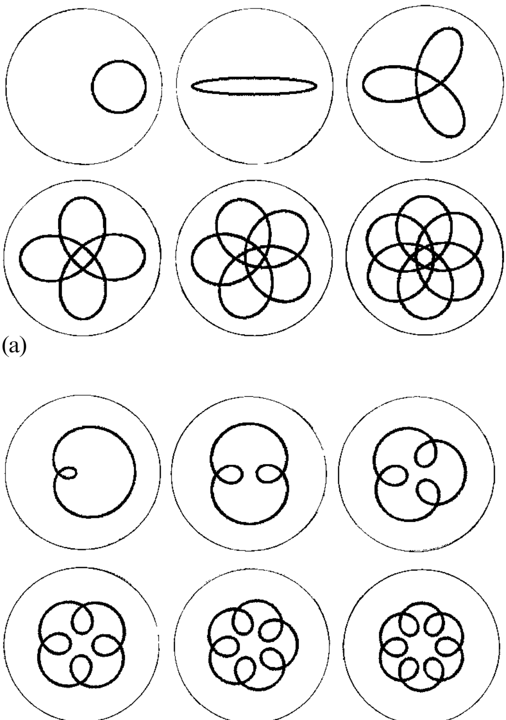

Figure 2. Cycloidal figures (a) outward lobes, 1 to 6; (b) inward lobes, 1 to 6.

The notion of believable objects was confirmed in two ways, which also provided tools for later analysis: we were able to make wire models of the perceived 3-D forms, and even rotate the models as display items; and we could make computer-generated stereo pairs to represent the 3-D forms and examine them at leisure. Details of the methods of preparation of the stereo pairs are given in the section on modelling.

3 Observations

The strongest and most interesting effects were seen with 1-lobe and 2-lobe inward displays, and both inward and outward 3-lobe displays (figure 2). All of these, when mounted on the disc and rotated, were seen as having clear 3-D forms, together with an internal movement, the forms persisting in spite of the ongoing motion. Alternative forms appeared and changed from time to time as is usual with ambiguous figures, but strong impressions of depth remained.

Similar 3-D effects were seen in the other displays when rotated. But in these more complex forms more variation was seen, with less persistence, giving a succession of 3-D forms in movement, seen clearly for a few seconds then replaced by others. Sometimes the more complex displays were seen to drop back into 2-D, as for example the 6-lobe outward, which seemed to flatten onto the central hexagon. With figures of middle complexity, one or other 3-D aspect would dominate for a while. We describe the observations of the 4-lobe outward as an example.

The 4-lobe outward display when rotated produced more complexities and ambiguities than the 3-lobe figure, and more also than the 5-lobe and 6-lobe figures. The more complex percepts constantly changed, with brief periods of clear definition. One form was rather like a ship's propeller, the lobes all twisted the same way, tumbling, half-tilted in depth to the plane of the paper, sometimes with rapidly alternating tilts. Also, it was seen to have internal motion along the curves, as in the 3-lobe outward. Another form was a percept of two broad loops, one closer to the observer and one further away, joined in depth by the other two arcs of the figure as they sweep across, rather like two kettle elements, one nearer and one further away. Again, there was a strong internal motion. (For interest's sake, we illustrate the propeller and the kettle element by stereos in figures 3d and 3e.)

3.1 *Investigation of the dominant forms*

All the displays when rotated were seen as having a variety of forms in motion, many of them having 3-D structure with motion in depth. For much of the time these forms followed one another in a procession of changes, in a multiple ambiguity with some appearing only briefly, others lasting longer, reappearing after a short while. But, as noted above, several of the displays (1-lobe, 2-lobe, 3-lobe inward, 3-lobe outward) were seen as having longer-lasting perceptual forms which could be examined in detail. We called these the dominant forms.

The main feature of the dominant percepts was the emergence of 3-D form: after a few seconds of observation of the rotating figure, it was seen to separate from the surface of the disc and take shape as a 3-D object, as if a rod had been bent and twisted into a complex but well-formed loop (with 1, 2, or 3 lobes, corresponding to the display in use). The form was maintained as it rotated with the disc, though even with these long-lasting percepts there was some switching between alternative well-defined forms. Within each variation the form was seen to hold firm, a persisting curved 3-D shape which rotated as the disc rotated. Often, the observer's eyes were dragged into following the curves as they moved with the rotation, so that attention followed along the curve around and through the depth of the perceived loops and twists.

During such an episode of following, the perceived form would usually persist. Casual shifts of gaze would often be accompanied by a flip to another variation of the percept, but they did not seem to affect the content of the available variations, nor to have any influence on the main effects of three-dimensionality. We therefore did not investigate them further.

As we have noted, the 3-D shape was persistent, yet it could not exactly be described as rigid: in addition to the rotation, there was an internal motion of the form. Braunstein and Andersen (1984) had described the motion in their 3-lobed figure as "twisting and bending", and "the loops will appear to twist independently in depth but remain connected". We would agree with these descriptions, but we can characterise more sharply the interplay of form and motion. We could see a 3-D form which did not itself change, and an apparent writhing by which the 3-D form twisted itself through its own loops in a sequence, maintaining itself as a fully shaped entity and yet progressing smoothly. We might compare this to the movement of a sidewinder snake, which carries itself over the desert sand in a wavelike motion. Thus we could say of the perceived 3-D form that it is not rigid but rather a fixed waveform which moves through the material of the figure without change of shape. For as long as it persists, the percept is constant but nonrigid, a pliant yet invariant form with an invariant motion.

3.2 *Why the 3-D form, and why also the 3-D motion?*

The question immediately arises: why does the percept take on a form which is three-dimensional rather than flat? Lost motion seems important, but how does it give rise to the third dimension?

Clearly, the sensed velocities of the different parts of the rotating figure are modified by the loss of information about motion. The modifications are then carried inward as distortions in sensed position and sensed velocity. The result is usually described, vividly, for example by Ullman (1984, 1986) as "misperception of the velocity field", but we would argue that this is not yet perception, it is still sensation. The retina has lost the sliding motion and, in its stead, signals another motion. The shapes of the curves would be sensed as changing to the extent that parts would be sensed as moving sideways without moving forward along their length. These movements are not compatible with the reality of a fixed display on a flat surface; this sets the problem which perception must solve.

We suggest then that the perceptual system interprets the sensory perturbations by finding a pattern of movement in depth which accommodates the variations in sensed velocity on the (flat) frontal plane, and by so doing attributes an invariance to the object perceived. The observer sees an illusion of organised movement along the curves of the display, and the curves are drawn out into depth. The resulting percept is of a 3-D curved object with movement along its curves, which, if it were to exist in reality, would project to the eye just the sensory information which it is indeed receiving from the rotating display. Thus the visual system constructs a percept which steadies and holds the flux of sensation for inspection or use.

3.3 *Observations with stereo pairs and models*

We were able to fix and extend our observations by constructing stereo pairs to represent the various 3-D forms observed, and also to represent alternative forms which could be derived from the same flat display figures but were not actually observed.

For example, the dominant aspect of the 3-lobed outward figure, as described above, can be seen in the stereo pair of figure 3a. (The 3-D effect can be obtained by

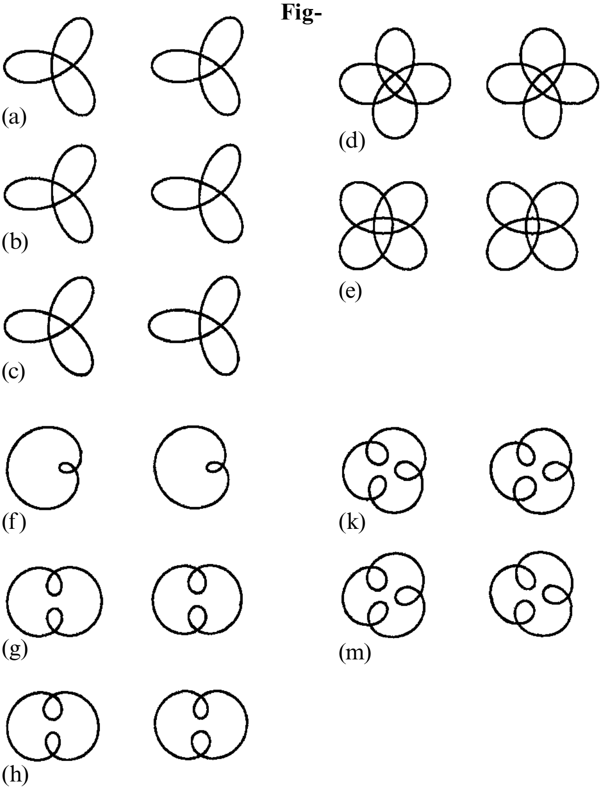

Figure 3. Stereo pairs representing stereokinetic forms and alternatives (a) 3-lobe outward, dominant aspect; (b) 3-lobe outward, interlaced lobes, not seen in stereokinesis; (c) 3-lobe outward, as on a dome, not seen in stereokinesis; (d) 4-lobe outward, ship's propeller aspect; (e) 4-lobe outward, kettle elements, seen in stereokinesis; (f) 1-lobe inward, twisted loop, dominant form seen in stereokinesis; (g) 2-lobe inward, two kettle elements, dominant form seen in stereokinesis; (h) 2-lobe inward, twisted loops, second percept seen in stereokinesis; (k) 3-lobe inward, ship's propeller; (m) 3-lobe inward, three kettle elements, as seen in stereokinesis.

the usual method of crossing the eyes to get four images, then fusing the central pair to form a single 3-D image.) The appearance is of a 3-D curved and twisted loop.

As alternative 3-D forms, the trefoil is shown in stereo (figure 3b) as being interlaced, with each of the rearward arms coming forward again through the lobes; and again in stereo (figure 3c) as if the lobes were draped over a dome. Neither of these alternative forms was observed in the illusion, though their stereos had been derived from the same flat figure as that of the dominant form.

(For the sake of interest we include stereo pairs for inward displays of 1, 2, and 3 lobes. The 1-lobe dominant form appears in figure 3f; the two chief forms which alternate in stereokinesis appear in figures 3g and 3h; and two prominent alternative stereokinetic forms of the 3-lobe display appear in figures 3k and 3m.)

The stereo images have the form, but of course they lack the writhing movement which was the second important component of the illusion. To go further into the relation between form and movement, we rotated models (in wire) of some of the stereo forms.

We mounted the model of the dominant trefoil, stereo 3a (see photograph, figure 4) on a disc in such a position that when viewed along the axis of rotation it would project a representation of the display figure, though some depth was still seen. When rotated, the model showed not only the same form as that aroused by the flat display, but also the illusory internal motion.

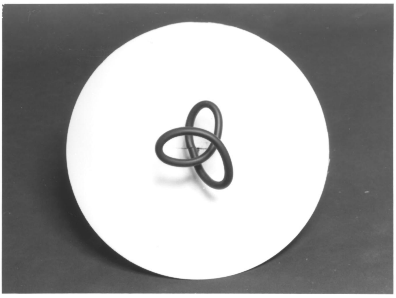

Figure 4. Model of the dominant stereokinetic form of the 3-lobe outward display.

The models of 3b and 3c had a different form but, when they were rotated, the same form and internal motion was seen as for that of 3a. The real forms of the models (interlaced or dome-like) were replaced by the dominant illusory form and motion.

Thus we had four objects: the flat drawn display, the model of the dominant stereokinetic form, the model of the domed form, and that of the interlaced form. If any of these objects was observed monocularly along the axis, when stationary, it was perceived as flat or nearly flat. When rotated, all were perceived as a form in depth, but it was the dominant stereokinetic form; for at least three of the four stimulus objects, the form perceived was not their own. We suggest that when other depth cues are weak the depth and motion in the percept are determined by the combination of motion sensed and motion lost in the stimulus. *The perceptual need to resolve the inconsistencies of sensed motion then takes precedence over the weaker cues of flatness or of the actual depths and forms of the models.*

4 Conclusion

Constructions of this kind are surely not limited to the stereokinetic effect. An example can be seen in the work of Kersten et al (1997), who seem to be dealing with closely related illusions, although they express their findings in terms very different from ours. Using computer-generated displays to represent objects and their cast shadows, they introduced variations in speed and distance between 'object' and 'shadow'. Subjects perceived apparent motion in depth of the objects, controlled by the sensed motions of shadow and object; they even saw the object 'bounce' when the shadow touched it and then moved away. Kersten et al explain their results in convincing detail; in our more generalised terms, the apparent status (as object and shadow-on-a-surface), the apparent motion in depth, and the perceived bounce, would all come about as perceptual constructions accounting for the sensed motions on the flat display screen of the computer.

Two questions of general interest arise from our study, one concerning the importance of rigidity and the other relating to the direction of processing in perception. The role and action of the rigidity principle was clarified by discussions between Braunstein and Andersen (1984, 1986) and Ullman (1979, 1984, 1986). Both agree that rigid motion of objects may be an important regularity exploited by perception, and that the question of its use in relation to other principles is an empirical question, though Ullman appears to attribute greater significance to rigidity as a basis for recovery of structure from motion.

We suggest that form, though important, is only one factor among many. In our observations we saw many illusory forms which were clearly defined and persistent; evidence pointing towards rigidity. Yet the persistent forms were also subject to internal movement, proving that rigidity, as an explanation, is not enough. Perhaps invariance, as suggested by Gibson (1968, 1972) is a more fundamental principle and more descriptive of our results, since it covers both the persistence of the (nonrigid) form and the persistence of the wave motion which disturbs it. The form which is perceived is nonrigid, changing in a squirming motion, but it nevertheless persists; the time-and-motion behaviour of the perceived wave also persists, as a continuous cycle of the same sequence of forms.

We can say that the forms and behaviour in the percept are invariant and matched to a real invariance in the spatiotemporal pattern of the sensory stimulus, modified as it is by lost motion and motion found. It would be easy to suppose, as Gibson did, that the perceptual invariance is derived from that actually contained in the sensory input, but the percept carries distinctive structures and motions which were not in the source. Unlike Gibson, we suggest that the percept is not passively derived from the input, but rather from an active matching process between tentative perceptual structures and sensory input. *Thus the percept would be constructed so as to match the input rather than being derived from it*. And a measure of match would be to minimise the residual invariance in the percept. An invariant percept would indicate that the system has locked onto invariant characteristics of the input.

With certain stimuli more than one invariant set of relationships may be identifiable. This would account for the multiple (ambiguous) percepts described earlier.

This analysis, in terms of match rather than derivation, is strongly reminiscent of Gregory's notion of 'perceptual hypotheses' (Gregory 1970, 1997). Such hypotheses attribute an active role to perception in the interaction of bottom–up and top–down processes. We see our study as an example of such hypotheses operating at the level of what might be called 'primary' perception: that is, a stage at which the basic shape and motion of the percept, illusory or veridical, are being formed in relation to the sensory evidence.

Sinha and Poggio (1997) ask how the brain strikes "a compromise between sensation and, for want of a better term, hallucination?"; and further, how expectations are combined with sensory information to yield the overall percept. Perhaps we should reply to their questions by suggesting, as we have done before (Wilson et al 1983) that brain processes are circular as much as up-and-down; that sensation feeds and guides perception but does not appear in it; and that perception does not compromise with sensation but uses it to remodel and qualify the current representation of the world.

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Appendix: The programs for drawing displays and stereos

We used a computer to draw our display figures, and then adapted the program to produce stereo pairs which could be compared with the illusory 3-D percepts.

The cycloidal curves, which we required were of the form shown in figure A1, the curve being defined by

$$x = r_1 \cos\theta + r_2 \cos\phi\,,$$

$$y = r_1 \sin\theta + r_2 \sin\phi\,,$$

where $\phi = (n+1)\theta$, n is the number of lobes; setting n negative would draw external lobes; r_1 and r_2 are chosen to get well proportioned figures.

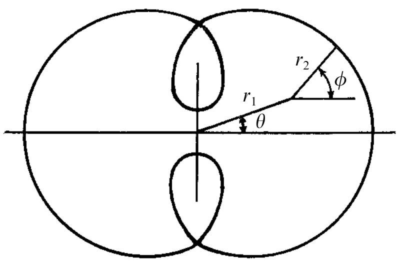

Figure A1. Construction of the cycloidal forms.

We wrote the programs in BASIC, to draw the figure on screen and then dump it to the printer. To get a broad line, the figure was drawn repeatedly on screen, each time with the origin displaced to a new position on a circle of radius half the required line width. With a sufficient number of positions, the gaps fill in.

To draw the stereo pairs, a short program was written to use the drawing routine twice, thus drawing the two figures; the figures are spaced apart by moving the origin along x or y between the two printings. Stereo depth is provided by adding to the x or y calculation (ie in the same direction as the shift of origin) a formula for disparity, which will shift the position of each printed point in the second figure by a small distance proportional to the height at which it should be seen.

In deciding what heights to draw, we found that by observing the illusory form carefully we could allocate height according to delightfully simple formulae [$\sin n(\theta)$, $\cos n(\theta)$, etc] and soon obtain a good representation of the observed stereokinetic form.