THE VARIOUS APPEARANCES OF A ROTATING ELLIPSE AND THE MINIMUM PRINCIPLE: A REVIEW AND AN EXPERIMENTAL TEST WITH NON-AMBIGUOUS PERCEPTS.

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Introduction

The so-called stereokinetic phenomena, of which the rotating ellipse is an instance, are among the early demonstrations that the visual system can extract three-dimensionality (3-D) from moving two-dimensional (2-D) stimuli (MUSATTI, 1924; RENVALL, 1929). Striking impressions of „real" rigid three-dimensional (3-D) objects can be produced by 2-D patterns rotating at uniform speed on the frontal plane around an axis normal to the image plane (the „z" axis), and describing perfectly circular trajectories.

The early explanations of the phenomena of MUSATTI (1924,1931) in terms of our past experience with rigid objects and of RENVALL (1929) in terms of „good form", appeared unsatisfactory. But these phenomena pose quite a problem also to modern theories of structure from motion.

Because these stimuli are already „rigid" non deforming 2-D figures, the 3-D percepts they produce cannot all be explained by a „rigidity assumption" (ULLMAN, 1979,1984a; HILDRETH et al., 1990) nor by any other derived theory (HOFFMAN and BENNET, 1985,1986; KOENDERINK, 1984; NORMAN and TODD, 1994; POLLICK, 1994; DOMINI and CAUDEK, 1999; TODD and PERROTTI, 1999).

Because they have a uniform surface and rotate around the axis of sight, the 3-D percepts cannot be explained by theories based on the velocities of the „local structure" of the surface (BRAUNSTEIN, 1976; BRAUNSTEIN and ANDERSEN, 1981, 1984; BENNETT and HOFFMAN1985; SHULMAN and ALOIMONOS,1988; LAPPIN and CRAFT, 2000).

However, it has been shown that an alternative hypothesis based on a perceptual process of Velocity Difference Minimisation (VDM) can explain various stereokinetic phenomena (ZANFORLIN, 1988a,b; BEGHI et al., 1991a,b; ZANFORLIN and VALLORTIGARA, 1988), and some percepts produced by a rotating ellipse (ZANFORLIN, 1988a; BEGHI et al., 1991b).

While most stereokineic stimuli produce a single percept the rotating ellipse produce a sequence of different percepts and poses the most interesting theoretical problems.

I will show here how the same hypothesis can be applied systematically to explain all the various percepts produced by a rotating ellipse.

Moreover, as a further test of the hypothesis, I will show how the various percepts can be disambiguated so that different unique percepts can be obtained by adding other stimuli to the uniform ellipse and under what conditions a spheroid can be perceived.

But before presenting the hypothesis I will review the various percepts produced by the rotating ellipse and the previous hypotheses advanced to explain some of the phenomena.

The impressions produced by a rotating ellipse

When an ellipse of average eccentricity and uniform colour is rotated slowly (approx. 15 cycles per minute) on the frontal plane, (see fig. 1a), it induces the following percepts:

1) at first all observers report just „a flat rotating ellipse" (MUSATTI, 1924; MEFFERD, 1968a,b; BRESSAN and VALLORTIGARA,1986; VALLORTIGARA et al.,1988);

2a) after approximately 80 seconds of inspection, the ellipse appears to deform and take on an amoeba-like movement (see fig. 1b.) (MUSATTI, 1924, 1955, 1975; RENWALL, 1929; WALLACH et al. 1956; MEFFERD, 1968a; VALLORTIGARA et al., 1988);

2b) at the same time the figure appears to maintain its „orientation in space" during rotation (MUSATTI, 1924, 1955). For example, in figure 1b, point A always appears to the left, point B at the top, and so on;

3) on continuing inspection, the elastic appearance vanishes and the ellipse appears as a rigid circular disc tilting back and forth in depth (MUSATTI,1924, 1955; RENWALL,1929 MEFFERD, 1968a; VALLORTIGARA et al., 1988; TODOROVIC, 1993;

4) thereafter, the disc vanishes and the ellipse may appear as a solid and rigid ellipsoid, an egg-like object, tilted in depth and of well defined length (MEFFERD, 1968a; VALLORTIGARA et al., 1986,1988; BRESSAN and VALLORTIGARA, 1986,1987; BEGHI et al.,1991b).

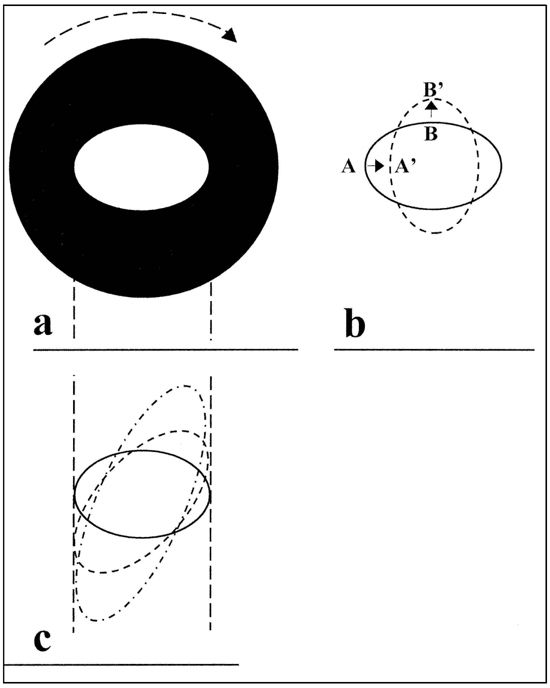

Figure. 1 a-c: a) Ellipse of uniform surface set on a larger rotating disc.
b) The apparent deforming ellipse; point A and B maintain their apparent orientation in relation to the ellipse centre.
c) Ellipse as a 2-D projection of an infinite number of solid ellipsoids seen from above.

5) all these appearances alternate with prolonged observation (MEFFERD, 1968a,b; BRESSAN E VALLORTIGARA, 1986, 1987; VALLORTIGARA, et al.,1988).

6) the percepts produced by the rotating ellipse and observed so far are all projectively compatible with the 2-D moving figure. It is therefore quite surprising that no one has yet reported perception of a further 3-D object, that is also projectively compatible with the rotating ellipse: the spheroid. As the ellipsoid is the solid produced by rotating an ellipse around its major axis, the spheroid is the solid produced by rotating an ellipse around its minor axis. This type of ellipsoid is also known as an „oblate spheroid“ or geoid, but it will simply be called „spheroid” here. The fact that this percept is not numbered among those produced by a rotating ellipse may be due to limited observation time, but this appears unlikely, and it raises an interesting theoretical problem.

Previous explanations of the phenomena

1) The initial perception of an ellipse as a flat, rotating 2-D figure, does not appear to require any explanation, as none can be found in the literature. As the subjects are reporting a percept that corresponds to what is „really" there, the fact does not seem to require any explanation. But, in the light of the explanations given by various authors of the subsequent elastic phase, further comment would appear necessary.

2) The elastic phase of the ellipse and the impression that it „maintains constant its orientation in space", are two phenomena tied up in the same explanation.

MUSATTI (1928) explained the apparently constant orientation of the moving ellipse by supposing that the movement of the contour points could be split into two components: one normal to the contour and one at a tangent to it and not detected, because each point along the uniform contour „can be confused with its neighbour". WALLACH and CENTRELLA (1990) speak of „identity imposition on the contour points on the basis of orientation".

The constant orientation of each contour point as a result of the „illusion of identity" or of „ identity imposition", makes the contour points appear to change their relative distance from the ellipse centre during rotation. Thus the ellipse appears to be elastic or deforming, as illustrated in fig. 1b.

WALLACH et al. (1956) and more recently, PROFFITT et al., (1992) and WALLACH and CENTRELLA, (1990) offered a similar interpretation of the effect. These authors assimilated stereokinetic phenomena to the Kinetic Depth Effect (WALLACH and O' CONNEL, 1953), in which relative movement between the various points of the pattern is also present. TAUBER and KAUFMAN (1977), ULLMAN (1984b), ROBINSON et al. (1985), WILSON et al. (1986), attributed the elastic appearance of the ellipse to „misperception" of the real movement of the curved contour due to limited „aperture" of neural movement detectors. So, for these authors the pattern of retinal stimulation is not that of a rigid figure, but that of a figure continuously changing shape.

The weak point of the „misperception" hypothesis for the elastic appearance of the ellipse is that it does not take into account how, in the initial phase, the ellipse can be correctly perceived as a rigid moving 2-D object. For, if the hypothesis of misperception of movement is correct, then this misperception should occur mainly in the initial phase of the perceptual process.

Thus, if the visual system can perceive the physical movement of the ellipse correctly at the beginning of the observation, then a supposed misperception cannot explain the subsequent elastic appearance of the ellipse.

3) After the deforming phase, that lasts for some time, the rotating ellipse appears as a rigid circular disc tilting backward and forward in depth while rotating.

MUSATTI (1924,1955) explained this as a „regularisation“ or minimisation of the differences in the relative distances between the centre of the ellipse and each contour point. These differences are „zeroed“ when all the contour points are at the same distance from the centre: i.e. the ellipse appears as a circular disc tilted in depth.

MUSATTI’s hypothesis is equivalent to ULLMAN'S (1979, 1984a) more recent „rigidity assumption“, and to the kinematic analysis of the rotating ellipse of TODOROVIC (1993) who reached the conclusion that the disc is „the only rigid object consistent with this stimulus”.

Thus, the rigidity hypothesis, as formulated by MUSATTI (1924), ULLMAN (1984) and TODOROVIC (1993), appears to be a satisfactory explanation for the disc appearance of the rotating ellipse.

4) But, on continued inspection, the rotating ellipse appears as a solid and rigid ellipsoid or an egg-like object, tilted in depth, of well-defined length, and longer than the major axis of the flat ellipse. This is a rigid object that the „rigidity assumption“ cannot explain. Firstly, because by equalising the relative distances among the various points of the pattern in successive projections, one will never be able to extract a configuration such as the ellipsoid. In fact, the longer diameter of the ellipse appears even longer when it is seen as the axis of the ellipsoid tilted in depth; i.e. the differences in length between the diameters of the ellipse are accentuated and not reduced, as prescribed by the hypothesis.

Secondly, the rotating ellipse, as shown in Fig. 1c, can be the 2-D projection of an infinite number of rigid ellipsoids of different lengths and tilts, while the perceived object has a well-defined height and tilt.

This last fact cannot be explained by a rigidity assumption, nor even by thinking of it as a „match“ between a „mental model“ (GREGORY, 1980) of a rigid ellipsoid and the perceptual input, rather than as a process of distance difference minimisation, unless some other ad hoc hypothesis is advanced regarding the ellipsoid’s apparent length. The rotating ellipse will match a mental model of a rigid ellipsoid of any length. To say that the apparent depth of a stereokinetic figure is due to a „default value” (CAUDEK and PROFFIT 1993; PROFFIT et al.,1992) does not resolve the problem, as any value can be a default value.

5) The rotating ellipse should also produce a spheroid percept. As the spheroid is a solid very similar to quite common objects such as oranges, apples or little squashed balls, it should easily be perceived on the basis of a „likelihood principle“ (HELMHOLTZ, 1910/ 1962; ROCK, 1983; CHATER, 1996) or the perceptual theory of „object hypothesis“ (GREGORY, 1980). But in spite of numerous researches on the rotating ellipse, the spheroid has never been observed or reported in the literature and this failure also requires some explanation.

In conclusion, to explain the elastic and rigid disc appearances of the rotating ellipse, two different hypotheses have so far been proposed; misperception of the contour movement and the „rigidity assumption“; and yet neither of these explains the ellipsoid or egg-like appearance with its well defined height nor the non-appearance of the spheroid.

1. Minimising relative velocity differences

The velocity differences minimisation (VDM) hypothesis derives from the „minimum principle“ of Gestalt theory (KOFKA, 1935; HATFIELD and EP-STEIN,1985; ZANFORLIN, 1988b). It assumes that the visual system will „organise“ the pattern of moving stimuli in two or three-dimensional space in such a way that the differences between the apparent relative velocities of „all“ the stimulus points are equal or minimal. For example, when two stimulus points move on the frontal plane and hence on the retina, at different velocities (such as the two extremities of a rotating bar in a radial position), the values (or the length of the vectors) of the two velocities can be equated by adding a „z“ or depth component to one of them.

Whether or not all the velocity differences of a complex pattern can be completely annulled („zeroed“), will depend on the characteristics of the stimulus pattern. But the hypothesis assumes that a minimisation process will occur, even if the velocity differences cannot all be annulled. When this happens, eithera 2- or 3-D elastic object may appear or a complex pattern may split up into two or more rigid „objects“ (sub-patterns) moving relative to each other.

The rotating ellipse

In applying the VDM hypothesis to the rotating ellipse, consider Fig. 2a, in which an ellipse of uniform surface is rigidly fixed to a rotating black disc with centre Q. (The particular position in Fig. 2a is chosen to make the reasoning clearer, but any other position of the ellipse on the disc will do).

As angular velocity is the same for all points of the ellipse, their linear velocity will be proportional to their radial distance from the rotation centre Q and thus point A moves faster than point B as shown by trajectories AN’ and BS’.

As reported in the introduction, at the beginning of the observation period all subjects describe the pattern as „a flat rotating ellipse“. This implies that the visual system perceives the correct physical speeds of the contour points of the ellipse. This can occur as the contour points can be „identified” in relation to the different axes of the ellipse or in relation to the difference of curvature.

1.1 The elastic ellipse

A cinematic reduction of the velocity differences of all the contour points can be obtained by a counter-rotation of these points along the ellipse contour and around its centre O, with the same angular velocity at which the centre O rotates around Q.

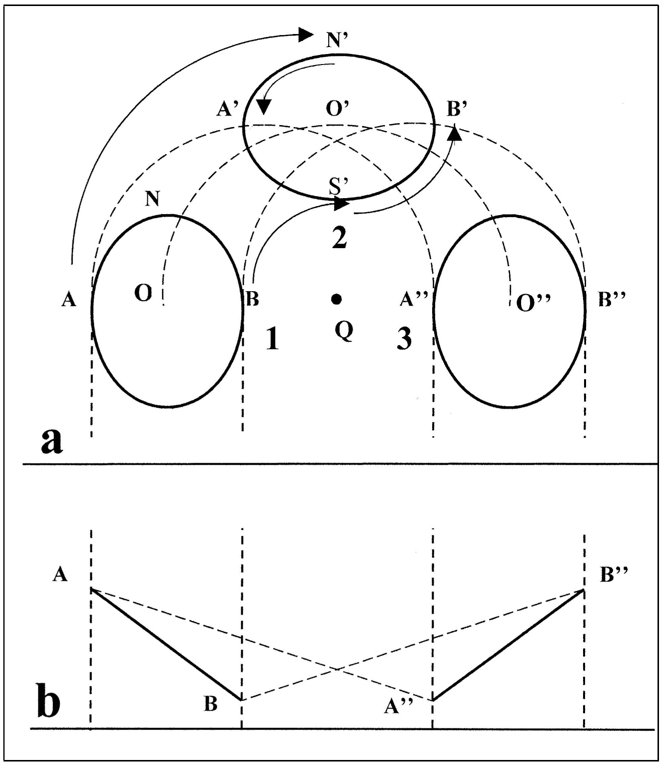

Figure 2 a-b: **a)** Schematic representation of the ellipse rotating around point Q. Nos. 1, 2, and 3 represent successive positions of the ellipse. A,A',A" represent the apparent trajectory of a perceptual point A on the ellipse contour. N'A' represents a counter-rotation of A along the ellipse contour around O, the centre of the ellipse. As result of this counter-rotation, the trajectories of all contour points form equal circles around Q. The contour points appear to maintain their orientation in space and change their relative distance from the centre O; i.e. the ellipse appears elastic. To "equalise" their velocity around O, the contour points have to describe circular trajectories around it. The ellipse will then appear as a rigid disc tilting in depth, and the trajectories of contour points around Q become elliptical.

b) The ellipse seen from above when it appears as a rigid disc. A B, and A" B" represent apparent positions of the disc in depth; A A", B B" represent apparent elliptical trajectories of contour points A and B around Q.

In Fig. 2a, perceptual point A will appear to describe trajectory A A' A" (A N' minus N' A'), perceptual point B trajectory B B' B" (B S' plus S' B'), and so on, for all the other contour points. These trajectories are all equal to each other and equal trajectories described in the same time space of a complete rotation yield equal speeds.

This counter-rotation is made perceptually possible by the fact that since the contour is of uniform colour, the various points can, so to speak, slide unnoticed along it. Obviously the counter-rotation is not perceived as such; what we perceive is the result; i. e. that point A, for example, always remain to the left of the centre O during the ellipse rotation and point B always to the right.

As a consequence of this process, the contour points appear to approach and recede from O during rotation of the whole ellipse around Q. Hence the apparent deformation or elasticity of the figure. Compare for example the relative distances of contour point A from O in positions 1 and 2.

1.2 The rigid disc

Perception of a rigid and tilting circular disc may be considered the result of an alternative minimal solution. As we have seen above, by counter-rotating around the ellipse centre O, the contour points describe equal trajectories in the same time-space around Q during a complete rotation. But their velocity along the trajectory is not uniform. Moving along the ellipse contour around the centre O at the same angular velocity, their vector velocity depends on their distance from the centre O; being higher in correspondence with the major diameter and lower with the minor.

But, the velocity of all points can be made uniform by adding to the vector of each point a depth component proportional to its distance from the centre O.

Addition of the depth component to the velocity of the contour points, transforms the apparent movement of approaching and receding from the centre O intoapparent movement in depth, while maintaining constant their distance from O; the ellipse appears as a circular disc tilting in depth during rotation around Q . See Fig. 2b.

1.3 The ellipsoid

Let us now suppose that while the ellipse rotates around the rotation centre Q, the contour points counter-rotate, not along its contour, but along a shorter circular trajectory across the uniform surface and centred on the longer axis of the ellipse. The circular trajectories will complete amodally behind the ellipse surface. (See for example, in Fig. 3a the hypothetical trajectory of point P P' P'').

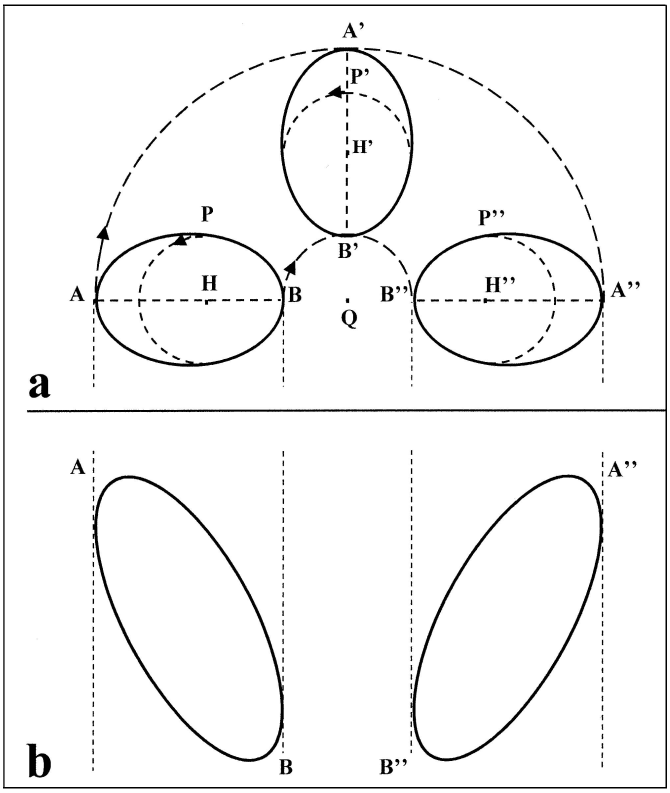

Figure 3a-b: a) The contour points of a rotating ellipse, instead of counter-rotating along the ellipse contour, as in the previous case, may appear to counter-rotate in a circular trajectory, P P' P'', across the ellipse surface and around a particular point H of the ellipse axis A B. In so doing its velocity around Q will appear equal to that of H. If all the contour points are considered as moving in the same way, each one will appear to have a velocity equal to a corresponding point along the ellipse axis. All the points along the ellipse axis have different velocities on the frontal plane; these will be equated by displacing the ellipse axis in depth as a rotating bar (see appendix). As a result the ellipse will appear as an ellipsoid slanted in depth.

b) The apparent ellipsoid seen from above. When the ellipse axis is displaced in depth and the contour points counter-rotate around it, the "object" appears solid and of a well defined length.

With a circular counter-rotation, all the contour points maintain their relative distances from each other and a constant distance in relation to the major axis. So, no elastic appearance is possible. During this counter-rotation all the contour points equalise their velocities to a particular point on the major axis of the ellipse; i.e. their centres of counter-rotation. [In Fig. 3a, if r = rotational velocity, the velocity of point P' is: vP' = rQP' = r(QH'+H'P') and when counter rotation is subtracted, we have vP'= (rQH'+rH'P') – rH'P' = rQH'].

The velocity of each point of the axis, on the frontal plane, is different depending on its radial distance from the rotation centre Q. But the different velocities of all the points on the axis, and hence the velocities of all the contour points, can be equated by adding to their vectors a proportional depth component. To equate the different velocities of the axis points is the same problem as equating the different velocities of all the points of a rotating line segment or a bar. This problem has already been dealt with in previous papers both intuitively using geometry and analytically (ZANFORLIN and VALLORTIGARA, 1988; BEGHI et al. 1991b). So, I will here describe briefly only one of the possible procedures that can be found in Appendix 1.

When we add a „z" or depth component to the velocity vectors of all the points on the rotating segment, such that their apparent velocity will be equal, the line will appear tilted in depth and 1.57 times longer than when perceived as stationary on the frontal plane. So the ellipsoid also appears 1.57 times longer than the stationary ellipse (see Fig. 3b). Its tilt, however, will depend on the value of the minor diameter of the ellipse, which in turn determines the breadth of the ellipsoid (BEGHI et al, 1991b).

When the apparent velocity of the contour points is equated with that of the corresponding points of the ellipse axis tilted in depth, they will describe circular trajectories normal to the axis. As a result, the ellipsoid surface will appear solid or curved in the third dimension; i.e. every point on the uniform surface of the ellipse acquires a precise and different depth value, in spite of the fact that, being within a uniform surface, they cannot be discriminated locally.

1.4 The spheroid

On the basis of the VDM hypothesis and by analogy with the previous case of the ellipsoid, the spheroid should be obtained by counter-rotating the contour points around the minor axis of the ellipse. As indicated by the dashed line A A" in Fig. 4, the contour points should initially describe elliptical trajectories on the frontal plane, across the uniform surface of the ellipse and around its minor axis. As these trajectories should be more „eccentric" than the ellipse contour, the contour points would appear to have greater velocity differences in relation to the ellipse centre, than when moving along the ellipse contour.

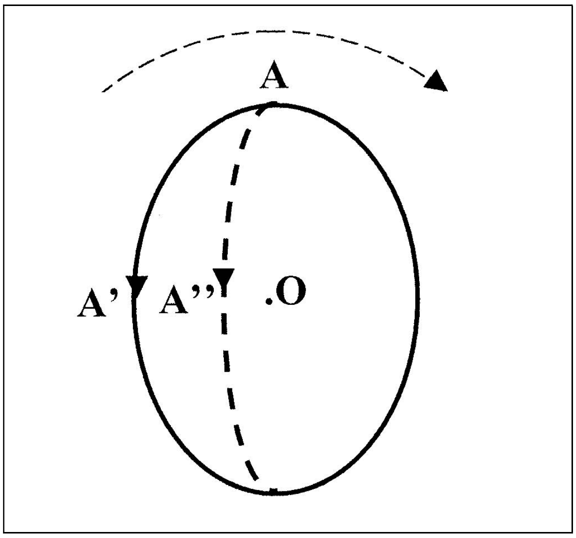

Figure 4: To obtain a spheroid, the ellipse contour points should counter-rotate around the ellipse minor axis describing an elliptical trajectory A A" on the frontal plane and across the uniform ellipse, instead of trajectory A A' along the ellipse contour. As the rotational velocity depends on the distance from the centre O, contour point A will clearly have a larger difference in velocity along trajectory A A" than along trajectory A A'. If the visual system tends to minimise velocity differences, the "preferred" trajectory will be A A' and not A A", and the spheroid will not be perceived.

Considering that in the rotating ellipse the angular velocities of the contour points are all equal, their velocity differences along the trajectory of counter-rotation around the centre O depend only on their distance from O. Thus contour point A has a maximal velocity in correspondence to the extremity of the major axis and a minimal velocity in correspondence to the minor axis. It is clear , as shown in fig 4, that the difference in velocity between the maxima and the minima is greater along trajectory A A” than along trajectory A A'.

So, on the basis of the VDM hypothesis, counter rotation should never occur along a trajectory of greater velocity differences when a trajectory with minor velocity differences is possible.

Thus, according to the VDM hypothesis, perception of a spheroid from a rotating ellipse of „uniform surface“ should be difficult, if not impossible. The fact that the spheroid has never been observed, in spite of much research on the rotating ellipse, may be of further support to the hypothesis.

In conclusion we may say, that instead of two different explanations for the elastic and rigid disc and none at all for the third egg-like appearance, as illustrated in the introduction, the VDM hypothesis explains all three percepts of the rotating ellipse (deforming figure, rigid disc and ellipsoid), as three different minimal solutions of a unique process, and the non-appearance of the spheroid as not being a minimal solution.

2 Unique minimal solutions for a rotating ellipse: a test of the VDM hypothesis

As we have seen, the VDM hypothesis not only can explain the various appearances of a uniform surface rotating ellipse, but it can make also quantitative predictions about the dimensions of the perceived ellipsoid that are in good agreement with experimental results, BEGHI et al. (1991b).

Another way to test the hypothesis would be to disambiguate the phenomena so that one, and only one, of the various appearances of the rotating ellipse is perceived, no matter how long the time of continuous observation.

Since the VDM hypothesis assumes that the visual system will attempt to minimise the velocity differences among „all the points of the configuration“, it would be theoretically possible to obtain configurations allowing unique minimal solutions simply by adding appropriate stimuli to the uniform ellipse.

2.1 The rigid and elastic disc

As explained in sections 1.1 and 1.2 above, the first minimisation produces two percepts: i) a deforming ellipse and ii) a rigid disc tilting in depth.

a) If we add a line segment to the ellipse along its minor axis, as illustrated in Fig. 5a,c, all the velocities of the configuration can be equalised by tilting in depth both the ellipse and the segment, as illustrated in Fig. 5b,d. Thus the segment will appear perpendicular to the disc (or to the cone as in 5d), both tilting in depth and rigidly connected like a radio antenna.

This configuration offers no other minimal solution, because, if we counter-rotate the contour points around the longer axis of the ellipse, we cannot eliminate nor reduce the velocity differences between the contour points and those of the segment; i.e. the segment appears to rotate relative to the ellipsoid.

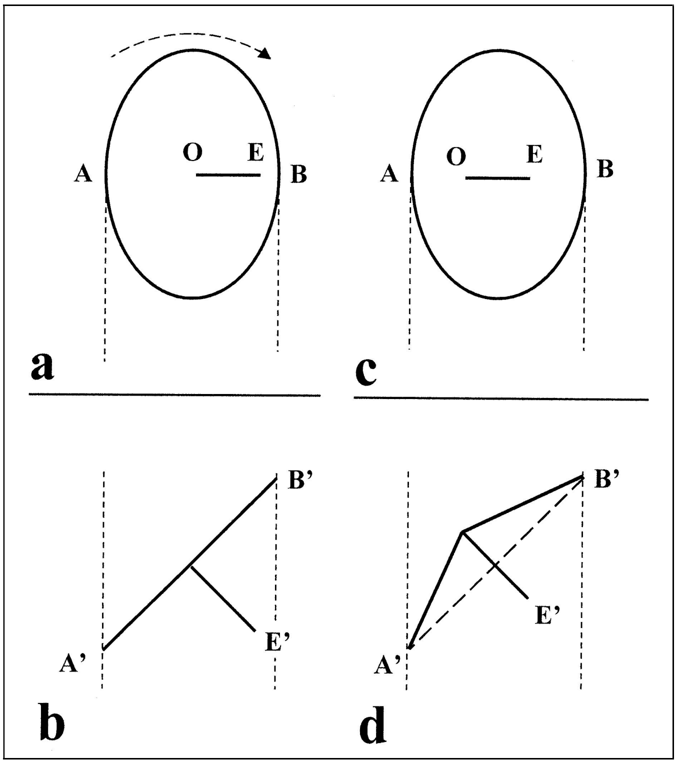

Figure 5 a-d: **a)** frontal view of an ellipse rotating around its own centre and with a line segment along its minor axis. On the frontal plane all the points of the segment O-E, due to their different distances from the centre O will have a different velocity from that of the contour points.

b) A tilted disc with perpendicular line segment seen from above. When displaced in depth all the ellipse contour points appear to have the same distance and the same rotational velocity in relation to the centre O' and in relation to the segment that appears as its axis of rotation .

c) Line segment drawn across the centre of the ellipse.

d) Vision from above of the ellipse displaced in depth which may appear as a cone with the apex formed by an extremity of the segment.

b) If the line segment is drawn along the major axis of the ellipse, the velocity differences between all the points of the configuration cannot be zeroed.

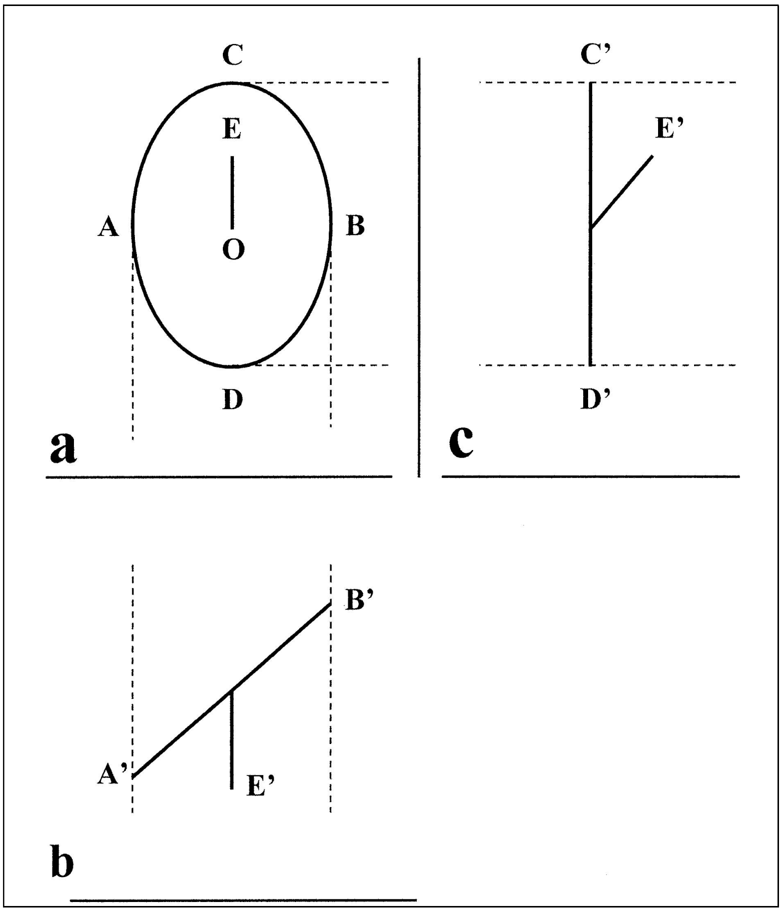

Figure 6 a-c: **a)** frontal view of a rotating ellipse with a line segment drawn along its major diameter.

b) A tilted disc with the line segment tilted in depth seen from above.

c) Lateral view of the ellipse on the frontal plane with the line segment tilted in depth. In no case will the segment appear as the axis of rotation of the ellipse and its extremity E will not have the same distance and thus the same velocity in relation to the ellipse contour points, see E" - A" B" in b) or E'- C'D' in c).

As illustrated in fig. 6a,b,c, in no case can the segment appear perpendicular to theellipse. Whether the ellipse appears as deforming on the frontal plane or as a disc tilting in depth, the distances and hence the velocities of the segment extremities from the contour points cannot be equalised.

Whether the ellipse will appear elastic or as a rigid disc, the segment will appear to rotate above it as an independent object; that is, a non-rigid configuration.

If the contour points counter-rotate around the major axis of the ellipse, a transparent ellipsoid should appear with a segment inside it along its major axis. Although this solution eliminates all the velocity differences, it is not easily perceived because the trajectory of the contour points across the surface of the ellipse may be impeded by the segment interrupting the uniformity of the surface.

Thus, addition of a line segment along the major axis of an ellipse prevents zeroing of all velocity differences, nor does it allow a unique minimal solution, with the result that at least three different percepts are possible.

2.2 The ellipsoid

If a semicircle centred on the longer axis of the ellipse is added, as illustrated n Fig. 7a, the only possible minimal solution of the configuration will be an ellipsoid. The semi-circle appears to complete itself „amodally” behind the ellipse surface, and all its points counter-rotate around the ellipse major axis as do all the other contour points of the ellipse.

Counter-rotation of the ellipse contour points along the ellipse contour will make the semi-circle appear as an independent object rotating above the ellipse surface; not a minimal solution. So that only the ellipsoid will be perceived. Addition of a semi-circle may also facilitate perception of an ellipsoid with the segment along its axis, as shown in Fig. 7b.

2.3 The spheroid

Addition of a semicircle to the ellipse not only produces a configuration with a unique minimal solution, it may also facilitate counter-rotation of the contour-points around the major axis rather than around the ellipse contour. If this is the case, it may be that addition of a semi-elliptical line around the minor axis of the ellipse, as illustrated in Fig. 7c, will induce perception of a spheroid. Alternative perception of this configuration would be an elastic ellipse or a tilting disc with a semi-elliptical line rotating above; i.e. a solution that does not annul all the velocity differences .

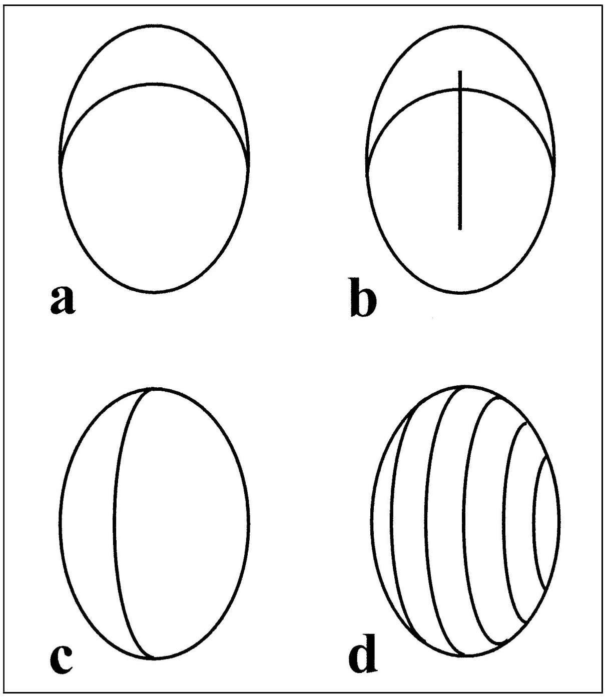

Figure 7 a-d: **a)** Ellipse with a semi-circle centred on the longer diameter that appears as a solid ellipsoid when set in rotation.

b) Ellipse with a semicircle and a line segment centred along the major diameter that appears as a transparent ellipsoid with a bar in the middle.

c) Ellipse with a semi-elliptical line centred along the minor diameter. The line appears either rotating with the ellipse on the frontal plane or rotating above a tilting disc.

d) ellipse with several semi-elliptical lines that appear as a spheroid.

3 Experimental control of the hypotheses of unique minimal solutions

The predictions of the VDM hypothesis as regards the unique minimal solutions illustrated above were tested by presenting observers with the various configurations described in the previous section. Since there was a large number of different configurations, these were divided in two groups and tested in different experiments using the same set up and the same procedure.

Apparatus and procedure

A black cardboard disc 30 cm in diameter was stuck onto a metal disc rotated by a variable-speed motor. After some preliminary trials the motor-speed was set at 15 revolutions per minute.Stimuli consisted of white cardboard ellipses that could be stuck to the larger black disc by means of small magnets. Room illumination was kept at 10 lux so as to prevent perception of the cardboard texture, but sufficient to allow subjects to locate the rotating disc and see the moving pattern clearly.

Subjects were seated facing the rotating disc with their head coaxial with the rotation centre and at distance of 2 m. They were asked to observe monocoularly the rotating figure continuously for 3 minutes and describe what they perceived and the changes in appearance as soon as these occurred.

Configurations were presented centred in the rotating disc and in randomised order, with an interval of one minute between presentations. After the first 3 minutes of presentation, configurations were set in other positions on the disc and variously orientated, in order to check for any position effect. The various appearances, their order and length of duration were recorded for each configuration.

Subjects were 10 psychology students with normal or corrected to normal vision and naive as to the aims of the experiment.

Experiment 1

To test the predictions made in section 2.1a and b, (whether rigid or elastic configurations according to which diameter the line segment is set), the subjects were shown the following configurations:

1a) Two ellipses made out of uniform white paper with the major diameter D = 6 cm and the minor diameters d = 5.2 and = 4.2 cm respectively. A line segment 1.5 cm long and 2 mm wide was drawn along the minor diameter with one extremity coincident with the ellipse centre, as in Fig. 5a. Ellipses of different eccentricity were presented to check whether ellipse eccentricity had any effect on the predicted results.

1b) Two ellipses the same sizes as above, but with a line segment 2 cm long centred along the minor axis, as in Fig. 5c, were also presented, to check whether the position of the line segment made any difference.

2a) Two ellipses the same sizes as above, but with a line segment 2 cm long drawn along the major axis with one extremity coincident with the ellipse centre, as in Fig. 6a.

2b) Two ellipses the same sizes as above, but with the line segment centred along the major axis.

Results

For all configurations an initial impression of a rotating flat disc lasting an average 16.6 seconds (s.d. 8.4), was reported by all 10 subjects.

For the remaining time of the 3 minutes of continuous observation, the impressions reported differed for the various configurations, as predicted by the hypothesis.

i) Configurations 1a,b) with the segment on the minor diameter, were perceived by all 10 subjects as rigid and unchanging for the entire observation time, as predicted by the hypothesis.

Configuration 1a) was described as a rigid disc with a perpendicular stick in the middle that moved solidly with the disc, like a radio antenna tilting in depth during rotation. Configuration 1b) was described as an „umbrella" or a cone with a stick rigidly connected to it in the middle. No difference was observed with ellipses of different eccentricity.

ii) Configurations 2a,b), with the segment along the major diameter, were described by all 10 subjects as non-rigid and changing during the continuous observation.

The types of objects produced by the different configurations were also in accordance with the predictions of the hypothesis .

Configuration 2a produced two different impressions: a deforming ellipse lying on the frontal plane or a disc tilting in depth. In both cases the segment appeared to be not rigidly connected but rotating like a clock-hand on top of the ellipse. The two impressions alternated during observation: deformation was observed for a total average time of 114.5 (s.d. 38.4) sec (63% of the observation time) with the less eccentric ellipse (d=5.2), and for 99 (s.d. 26.5) sec (55% of observation time) with the (d=4.2) ellipse; a difference not significant with t test.

Configurations 2b) also produced two different types of impressions: a flat deforming ellipse with the segment rotating above it on the same frontal plane and a deforming cone with the segment rotating at a tilt in the middle of the cone. Some subjects described the percept as a „rubbery umbrella" .

The two appearances alternated: the deforming ellipse lasted for an average total of 162.5 (s.d. 18.9) sec. (90.2% of observation time) in the less eccentric ellipse (d=5.2) and for an average total of 110 (s.d.30) sec. (60.5%) with the other (d=4.2), a difference statistically significant: t (9) = 4.011 p = 0.003.

In all cases the configurations 2a,b produced non-rigid and very unstable percepts as predicted by the hypothesis.

Experiment 2

To test the predictions made in sections 2.2 and 2.3, ellipses of the same dimensions as in the previous experiment were used and the same methods and procedure followed.

1a) Two ellipses with a major axis D = 6 cm and the minor axes d = 5.2 and 4.2 cm respectively with a semicircle centred along the major diameter of the ellipse as illustrated in Fig. 7a.

1b) To the ellipses described in 1a, a line segment was added along the major diameter as in Fig. 7b.

2a) To test whether addition of semi-elliptical lines would facilitate perception of a spheroid, 2 ellipses of the same sizes as before with a semi-elliptical line centred along the minor axis (see Fig. 7c) were presented.

2b) From preliminary observations, it had emerged that a single semi-elliptical line did not appear sufficient for perception of a spheroid, so 2 more ellipses of the same size as the previous ones, with a series of semi-elliptical lines centred along the minor axis were presented, as illustrated in Fig. 7d.

Results

1a) All 10 subjects described the rotating ellipse with a semi-circle as a rigid ellipsoid. The impression arose within a few seconds (average time 5.4 sc., s.d. 1.2). and lasted throughout inspection time. No subject reported the alternative, projectively possible, percept of a tilting rigid disc with a semicircular line rotating above it.

1b) All the subjects described the configuration as a transparent ellipsoid with a bar in the middle. A unique minimal solution that could not be obtained without the semicircle.

2a) For configuration 2a) no subject reported the impression of a spheroid. The ellipse with a semi elliptical line appeared either as a „flattened ellipsoid“ rotating on the frontal plane or as a thick disc (similar to a „frying pan“), tilting in depth and maintaining its orientation in space with the semi-elliptical line rotating on top of it.

2b) For configuration 2b) all subjects reported seeing the ellipses with several semi-elliptical lines as a solid spheroid for an average of 138 sec (s.d. 32), that is, for 76 % of the inspection time. The percept alternated with the impression that ellipse and semi-elliptical lines rotated in the same direction as the black disc, with no impression of real three-dimensionality. Thus even by adding to the ellipse several facilitating semi-elliptical lines, the spheroid remain a percept difficult to obtain.

All these results also are in complete accordance with the predictions derived from the VDM hypothesis.

Discussion and Conclusion

The hypothesis that the visual system tends to minimise the relative velocity differences of moving stimuli (VDM), has here been shown to explain adequately all the various percepts produced by a rotating ellipse of uniform surface. The various percepts produced by the uniform ellipse can be considered as the results of different minimal solutions that alternate on prolonged inspection. The hypothesis also explains the non-perception of a spheroid (a projectively compatible solid), as such a percept is not one of the possible minimal solutions.

On the basis of the VDM hypothesis, it was predicted that, by adding opportune features to the ellipse of uniform surface, unique minimal solutions and thus unique and unambiguous percepts, would be obtained in many cases. Results of the experiments here reported are in complete accordance with the predictions derived from the hypothesis. Moreover it has also been shown that by adding appropriate semi-elliptical lines to the ellipse uniform surface a spheroid can be perceived.

As pointed out in the introduction, while MUSATTI's (1924, 1955) hypothesis and ULLMAN'S (1979,1984a) rigidity assumption, as well as the „likelihood principle“ (ROCK, 1983; CHATER, 1996) or the „object hypothesis“ (GREGORY, 1980), can explain only the elastic and the rigid disc appearances of the rotating ellipse, whereas the VDM hypothesis explains not only the ellipsoid with its depth value (a solid that the previous hypothesis could not explain), but also non perception of the spheroid; a solid that should be perceived on the basis of the likelihood principle.

As regards the likelihood principle a surprising hypothesis has recently been advanced by CHATER (1996). CHATER maintains that, in spite of the historical debate, the „likelihood principle” interpreted as the „most probable” object that could fit the stimuli and the Gestalt „minimum principle” should lead to the same results. The well defined length of the ellipsoid and the non perception of the spheroid, here reported, are clear instances that that the two hypothesis lead to quite different results.

Various other hypotheses of „structure from motion“ were not considered in detail here because, as mentioned in the introduction, they clearly could not be applied to sterokinetic phenomena.

Many of these hypotheses seek to solve a typical problem of Artificial Intelligence which, however, is quite different from the problem posed by the stereokinetic phenomena. That is, given the 2-D projection of a moving 3-D object, how and under what conditions can the real object that has produced those images, be recovered? This is equivalent to establishing the properties of an ideal visual system. When these hypotheses are tested, the limits and advantages of the visual system are pointed out but not explained.

Given that the human visual system may not be ideal (KOENDERINK and VAN DOORN, 1991; TODD and BRESSAN,1990), how does it „work"?

This is the problem posed by stereokinetic phenomena and it sounds quite different: i. e. given a 2-D moving figure that may be the projection of an infinite number of solid objects, how does the visual system produce those particular 3-D percepts and not others?

So far,the VDM hypothesis appears to be the only one which explains all the percepts produced by a rotating ellipse and why other projectively possible objects, such as the speroid, are not perceived. Moreover, the fact that the VDM hypothesis also provides an adequate explanation for a number of other phenomena of „depth from motion, would appear to make it a valid hypothesis for a wide range of phenomena produced by moving stimuli (BEGHI et al. 1991a,b; 1977a,b; XAUSA et al., 1997; ZANFORLIN et al.,1997).

Appendix

When a line segment or bar is set in rotatory motion on the frontal plane (i.e. attached to a black disc as the ellipse considered in this paper) the first impression that appears, after a brief inspection time, is that:

1) the segment appears to rotate around its own centre lying on the frontal plane;

2) on continuing inspection, the segment appears slanted in depth and longer than its length on the frontal plane (ZANFORLIN and VALLORTIGARA, 1988; BEGHI et al., 1991a).

1) The first impression can be explained by applying a minimum principle in analogy to RUBIN'S (1927) and DUNKER'S (1929) rotating wheel or to JOHANNSON'S (1974) vector analysis.

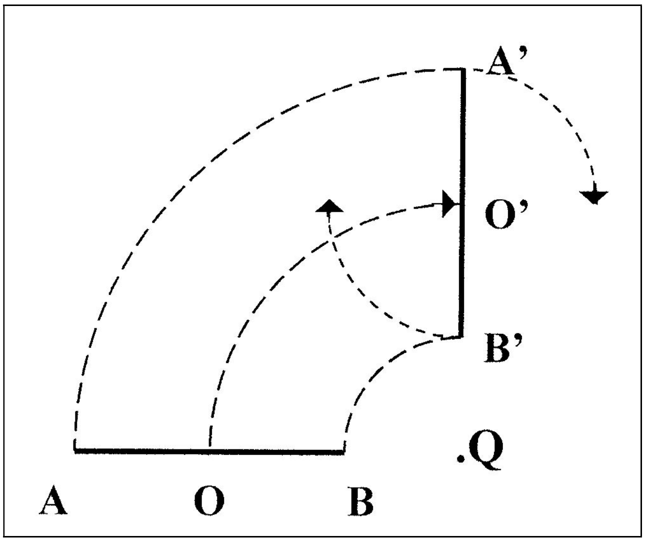

Figure 1 app: The line segment or bar AB rotates on the frontal plane around Q. The two extreme points A and B appear to rotate around O at equal velocity, while O moves around Q and describes a common component.

2a) With reference to fig. 1), AB is a line segment that rotates radially around Q; the velocity of each point of the segment differs according to its distance from Q. If we suppose that the visual system extracts a „common velocity", i.e. the velocity of the central point O, from the velocity of all the other points of the segment, the velocity of the extremes A and B will appear equal in absolute values (and opposite directions) in relation to O.

This may be considered a process that minimises the absolute values of the relative velocity differences between the points of a segment. Obviously the velocities of A and B still differ from that of O, as the segment appears to rotate around O. The operation is equivalent to a transfer of the reference system origin to the moving centre of the segment.

2b) The appearance of the rotating segment slanted in depth may be explained by a further step in the same process, that equalises the velocities of all the points of the segment by adding a depth component.

One way of explaining how all points of a segment can equalise their velocity is to imagine that they all describe equal trajectories in the same time-space.

For this purpose we transfer the origin of the reference system to one extremity of the rotating segment in order to obtain a positive value for the relative velocity of all its points, as illustrated in fig. 2a).

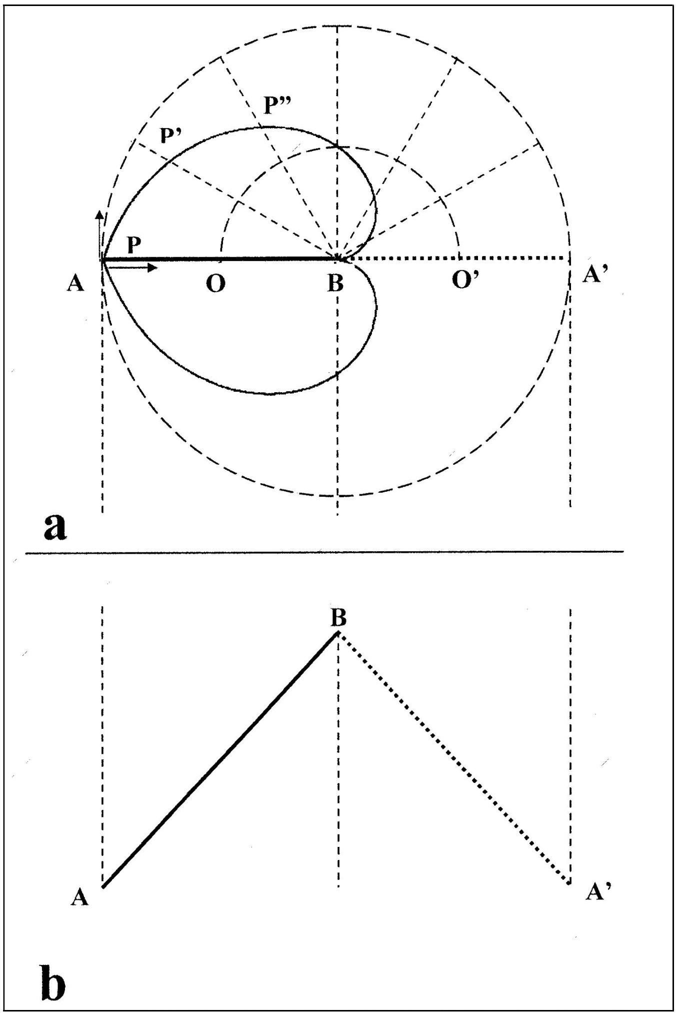

Figure. 2 a-b: a) The segment AB rotates around the extreme B. P, P', P",.. indicate the successive positions of a virtual point which, moving along the rotating bar at constant speed, describes a cardiode curve.

b) Schematic representation of the line segment, seen from above, when it appears tilted in depth.

Let us now consider a „virtual point“ P that moves at uniform speed from A to B along the segment during the first half rotation and moves back from B to A in the second half rotation, reaching the starting position after a complete rotation. The trajectory that the virtual point describes on the frontal plane, is a cardiode, and if each point moves in the same way along the segment starting from its position, they will describe an equal trajectory in a different position.

To determine the apparent length of the line slanted in depth, we may consider this cardiode (actually, we need only the first half) as the frontal projection of the trajectory described by a virtual point P' that moves along the segment slanted in depth at a uniform velocity; a velocity equal to the average of the relative velocity differences of all the segment points. To say that point P' moves at uniform velocity is equivalent to saying that all the points of the segment, since they describe an equal trajectory in the same time-space, show instantaneous velocity equal to that of P.

Let us go back to fig. 1 and note that if the segment is long 1, the maximum difference in relative velocity derives from the difference in distance between extreme A and centre O; i. e. 0.5. This is the same value as that of velocity point O in fig. 2, where the segment rotates around one extremity. Here the velocity of O is constituted by the mean relative velocity differences of all the points of the segment, since A = 1 and B = 0. If we attribute to point P, moving along the line slanted in depth, the same uniform velocity of O on the frontal plane (or of A and B in relation to O in fig.1), it will move, during the half rotation, a distance equal to the trajectory described by point O during the same half rotation. With equal velocities, equal distances are travelled in the same time. As the semi-circle described by O on the frontal plane is long 0.5 π (i.e. 1.57), then the segment AB, that is long 1 on the frontal plane, will appear 1.57 long when slanted in depth.

To generalise, as the length of the segment on the frontal plane and the velocity of its mid-point (or the velocity of one of its extremes in relation to its centre) are in constant ratio, whatever the length of a segment rotating on the frontal plane, it will appear 1.57 longer when slanted in depth to equalise the velocity of all its points. For a detailed analytical demonstration, see BEGHI et al. (1991a). For experimental results in accordance with theoretical predictions, see also ZANFORLIN and VALLORTIGARA (1988).

Summary

A review of the literature on ellipses of uniform surface rotating around the axis of sight shows that they produce various alternating percepts: a flat ellipse, a deforming figure, a rigid tilting disc and an ellipsoid (a cigar). The point is made here that the rotating ellipse should also produce another projectively compatible figure, that has never been observed: a spheroid (a little squashed ball). The various theories proposed to explain the phenomenon, such as „misperception“ of the real movement or the „rigidity assumption“ can explain only some of the percepts reported. A hypothesis is here presented based on a perceptual process that tends to minimise the relative velocity differences of all the points of the moving figure. This hypothesis

offers an explanation for all the various percepts reported and also for why the spheroid cannot be perceived. The theory also predicts how the rotating ellipse can be disambiguated to obtain unique percepts; i.e. how the rotating ellipse can appear only as a deforming figure or as a rigid disc, an ellipsoid or a spheroid. The experiments reported fully support the predictions derived from the hypothesis.

Zusammenfassung

Eine Überprüfung der Forschungsarbeiten bezüglich elliptischen, gleichmäßigen, um der Sichtachse rotierenden Figuren zeigt, dass die letzten verschiedene, nacheinanderfolgende Wahrnehmungen hervorbringen können: nämlich, eine Ellipse, eine sich verformende Figur, eine schrägstehende Scheibe und ein (zigarrenfömiges) Ellipsoid. Eine fünfte mögliche Wahrnehmung wird erwähnt, die aber bis jetzt nie beobachtet wurde: ein Sphaeroid, d.h. eine Figur die einer leicht plattgedrückten Kugel ähnlich ist. Verschiedene Theorien sind vorgelegt worden, um solche Phänomene zu erklären, wie zum Beispiel eine mögliche Fehlwahrnehmung vom Beobachter, oder auch eine Starrheitsannahme von seiten desselben. Solche Theorien können aber nur einige der oben erwähnten Wahrnehmungen erklären. Eine neue Theorie wird hier vorgestellt, die sich auf Wahrnehmungsprozesse bezieht, welche zu einer Minimierung der relativen Geschwindigkeitsunterschiede zwischen allen Punkten der sich bewegenden Figur führen. Diese Hypothese bietet eine Erklärung für die unterschiedlichen oben erwähnten Wahrnehmungen und der Unmöglichkeit der Wahrnehmung eines Sphaeroids unter normalen Umständen. Ferner sagt diese Theorie voraus, unter welchen Umständen die rotierende Ellipse eindeutigerweise nur als eine sich verformende Figur oder als eine starre schrägstehende Scheibe, als ein Ellipsoid oder als ein Sphaeroid wahrgenommen werden kann. Die vorgebrachten experimentellen Ergebnisse stimmen eindeutig mit den Voraussagen der Theorie überein.

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