Stereokinetic effects with sharp and fuzzy illusory contours

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Abstract. A black, 8-shaped pattern, whose centre of gravity is in the centre of a rotating disc, appears to split into two black discs rotating with phenomenal independent motion, orientation stability, and sliding of one on the other. The type of observed movement, the order of overlapping, and the extent of the stereokinetic depth in relation to the contour type and different dimensions of the pattern were investigated. The experimental data show that a fuzzy contour facilitates the stereokinetic effect. Furthermore, the extent of the stereokinetic depth has been found to be greater in case of fuzzy contour and vertical orientation of the pattern. These results are in contrast with the models in which this effect is considered as a problem of minimisation of distances or velocities. A vector model of the observed movement and an interpretation of the overlapping based on an energy approach are proposed. A tentative explanation of the stereokinetic depth for our patterns is put forward.

1 Introduction

In the current literature stereokinetic phenomena, first observed by Musatti (1924), are defined as "depth impressions evoked by certain two-dimensional patterns that have been rotated in the picture plane" (Proffitt et al 1992, page 3). Several explanations of these effects have been proposed, based on a variety of hypotheses involving different principles and different levels of the visual process.

Musatti (1955) put forward the hypothesis that three factors concur to produce the perceived effect: (i) an identity-figure illusion, an instance of the so-called 'aperture problem' (Hildreth 1984); (ii) orientation stability; and (iii) a rigidity assumption. Zanforlin and coworkers (Zanforlin 1988; Zanforlin and Vallortigara 1988; Beghi et al 1991) pointed out that the rigidity assumption cannot explain various observed instances of the stereokinetic effect, for example, a deforming ellipse or the so-called rotating-line effect (Mefferd and Wieland 1967), in which a line rotating in the frontoparallel plane appears to be deformed. Recently, Beghi et al (1991) proposed a model based on the hypothesis that the visual system minimises the differences in the relative velocities among all the points of a configuration moving on the frontoparallel plane. Differences of velocities among a set of points can be eliminated by adding to each point a velocity component along the axis orthogonal to the frontoparallel plane; this velocity component should in turn produce the depth effect.

Wallach and Centrella (1990) argued that the stereokinetic effect depends on two factors: the 'identity imposition' and the 'kinetic depth effect'. The 'identity imposition' can be illustrated by referring to figure 1, see over.

Suppose that the figure rotates; the rings then appear to move independently. A ring is a line of constant curvature each part of which can be superimposed to any other, thus a rotation around its centre cannot be perceived because there is no information leading to that perception. Even though the various parts of the figure are indistinguishable in the stimulation, nevertheless they are perceptually identified, that is, the parts that are in the same orientation with respect to the centres of the rings are

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perceived to remain the same. To quote Wallach et al, "in experience the ring consists of definite parts which move in relation to the other ring" (1956, page 51). According to Wallach, the combination of the identity imposition with the kinetic depth effect, that is, the simultaneous changing in orientation and distances among the perceptually identified parts, is enough to produce the stereokinetic transformation.

Proffitt and coworkers (1992) questioned the above explanations and suggested that the stereokinetic effect is a component of the kinetic depth effect. The former involves movements between the contours whereas the latter also involves movements within the contours. If this hypothesis is true then a depth effect should be also observed in the case of patterns translating across the frontoparallel plane. Indeed this effect has been seen in several experimental conditions (Proffitt et al 1992).

The experiment presented here concerns stereokinetic effects that can be produced by using the patterns shown in figure 2.

The case of the pattern in figure 2a was studied many years ago by Wallach et al (1956) and, strangely, forgotten, whereas the pattern in figure 2b is a novel variation on the former. Consider the 8-shaped pattern of figure 2a: we define its 'centre of gravity' as the equilibrium point under gravitational force, supposing a uniform distribution of matter. When this pattern is placed with its centre of gravity in the centre of a slowly rotating disc it appears to split into two black discs rotating, and sliding on each other, with phenomenal independent motion and orientation stability; the order of overlapping of the discs changes continuously, that is, each disc appears alternately to be behind or in front of the other. This phenomenon also implies the

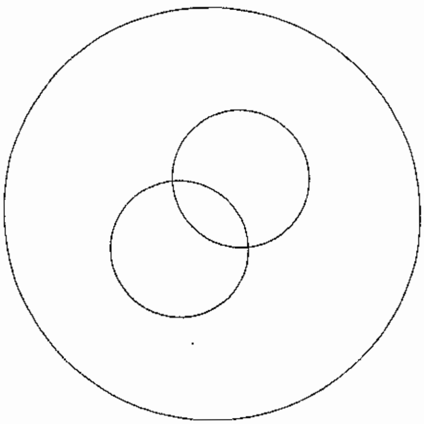
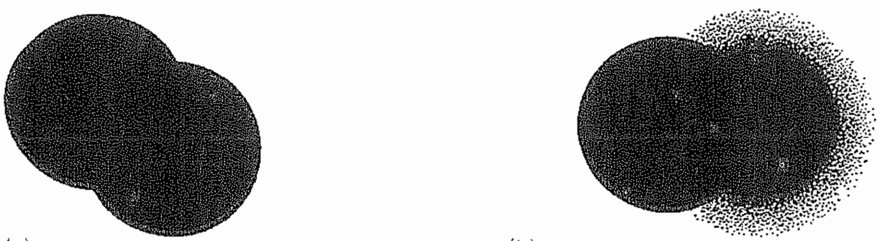


Figure 1. Two homogeneous rings on turntable. When the rings are turned at a moderate speed, they will first be seen to turn as a unit and sooner or later they will appear to move independently of each other (from Wallach et al 1956).



(a) (b)

Figure 2. (a) Pattern 1 and (b) pattern 2 used in the experiment. When the 8-shaped figures are turned, after a short delay a stereokinetic transformation occurs (see text for description).

formation of sharp subjective contours. In the case of figure 2b, where part of the contour is fuzzy, the same phenomena occur, but there is a definite order of overlapping, in that the phenomenal disc with fuzzy contours is seen prevalently in the foreground and a fuzzy contour appears also inside the other disc. These stereokinetic transformations are called kinetic perceptual completions (Metelli 1940). Metelli showed that if two discs of different colour, one of which is partially superimposed on the other, rotate then the partly covered disc is completed, that is, it appears to rotate behind the other as if it were a complete disc showing successive different parts.

Informal inspections based on the pattern presented in figure 2 showed that, after a short delay from the starting of the rotation, a more striking stereokinetic transformation occurs: the observer perceives one of the following three-dimensional (3-D) objects: an oblique truncated cone of a definite height, whose near and far faces are given by the two perceptual discs, or an inverted truncated cone whose major base is the disc in the foreground and whose minor one is part of the disc in the background. This depth impression is stronger in case of partially fuzzy contours (figure 2b), where the major base is always given by the phenomenal disc with fuzzy contours and the height of the object appears to be greater than in the case of figure 2a.

2 The experiment

The aim in the present work was to investigate the phenomenal evidence concerning the following points: (i) the kind of perceived movement which arises when the 8-shaped pattern is slowly rotating; (ii) the role of sharp vs fuzzy contours in determining the order of overlapping of the two phenomenal discs; (iii) how the dimensions of phenomenal discs modify the order of overlapping; and (iv) the strength of the depth effect as a function of the dimensions of the phenomenal discs, the type of contour, and the orientation of the perceived 3-D object with respect to the coordinate axes in the frontoparallel plane.

Regarding point (i), we intended to verify and make more precise, in a quantitative way, the informal observations by Wallach and co-workers (Wallach et al 1956; Wallach and Centrella 1990). If these informal observations were to be confirmed they would provide further evidence of the violation of the rigidity assumption. Regarding point (ii), we aimed to verify the following hypothesis: the introduction of a marginal gradient, eliminating or strongly reducing the nonhomogeneities in the stimulus, produces a transformation of a surface colour into a film colour (Kanizsa 1979). This transformation implies that, in our case, the phenomenal disc with fuzzy contours appears soft, and lighter than the sharp one. If the two phenomenal discs appear different, during the apparent movement one of them should rotate permanently in front of the other, leading to its completion, as in Metelli's original situation. If the informal observations regarding the prevalence in the foreground of the phenomenal fuzzy disc were to be confirmed, this would suggest that illusory fuzzy contours are somehow easier for the visual system to create (Kanizsa et al 1982).

The measurements of the strength of the depth effect [points (ii) and (iv)] were devoted first to the analysis of the strength of stereokinetic transformations more complex than perceptual completion; moreover we intended to verify whether the apparent height of the 3-D object depends on figural conditions such as type of contour, dimension of phenomenal discs, and the orientation along which this height is determined. If this is the case, since the differences in the relative velocities among all the points of the different configurations remain the same, interpretations claiming minimisation as a basis for the stereokinetic depth effect would appear questionable.

2.1 *Method*

2.1.1 *Subjects*. In this experiment we used a within-subjects design. Six adult subjects who were all volunteers and normal-sighted, participated in the experiments. The average age was 28 years. All the subjects knew the basic stereokinetic effects but were not aware of their purpose in the experiment.

2.1.2 *Material*. Four patterns were used in this experiment. Pattern 1 (see figure 2a) was a black 8-shaped figure with sharp contours on a white background. The 8-shaped figure could split into two discs, each of diameter 4 cm. Pattern 2 (see figure 2b) was similar to pattern 1, but part of the contour of the shape was fuzzy. Patterns 3 and 4 (see figure 3) were again black 8-shaped figures on a white background; each of them could split into two discs of different diameters, 4 cm and 2 cm, respectively. In pattern 3 (see figure 3a) the contour of the 8-shaped figure was sharp, whereas in pattern 4 (see figure 3b) it was partially fuzzy. All 8-shaped figures were photographic reproductions of drawings made with india ink; their centre of gravity coincided with the centre of rotation of the turntable. The diameter of the turntable was 20 cm.

2.1.3 *Apparatus*. The apparatus was an electric motor with the turntable placed on the rotation axis. The turntable was in the frontoparallel plane and its distance from the subject was 170 cm. The angular velocity of the apparatus was 20 rev min^{-1}, and the ambient light was kept constant and at low intensity during all experiments.

2.1.4 *Procedure*. Each experimental session consisted of four parts; during each part the same pattern was presented. In the first part the subjects performed a free inspection of the rotating pattern for 2 min. At the end of this part the subjects described what they saw. If the subjects reported spontaneously a phenomenal splitting of the shape into two discs the experimenter suggested to them the possibility of seeing a 3-D object. If this was seen the subjects reported the form of the object.

In the second part, if the subjects reported spontaneously a split of the figure into two phenomenal discs, they would press a key on a computer when the relative overlapping of the perceived discs changed. The time during which each of the perceived discs was in the foreground was automatically recorded and stored in the computer. The duration of this part was 2 min. After a short interval this trial was repeated.

In the third part the task of the subject was to determine the apparent depth between the two phenomenal discs (that is, the height of the 3-D object). We have used a simple method proposed by Wallach and Centrella (1990), in which the subjects evaluated the depth by means of the distance of two fingers aligned along the line of sight. Subjects were instructed to perform the measurement in two different situations: when the main axis of the shape was in the vertical orientation and when it was in the horizontal. There were two measurements for each condition. The order of presentation of the patterns was partly counterbalanced within the subjects.

(a) (b)

Figure 3. (a) Pattern 3 and (b) pattern 4 used in the experiment. When the 8-shaped figures are turned, after a short delay a stereokinetic transformation occurs (see text for description).

2.2 *Results and discussion*

All subjects reported, during the free-inspection period, both the splitting of the 8-shaped figures and the independent motion of two black discs, which slid on each other while maintaining orientation stability. In addition, at the end of the free-inspection period, the subjects perceived a definite 3-D object, as described in section 1. This stereokinetic depth effect was stronger in the case of the figures with fuzzy contours, and for each pattern it was stronger when the main axis of the shape was in the vertical orientation. Furthermore, the effect was weaker for patterns which split into two discs of different size.

Next, the quantitative results of the measurements described in section 2.1.4 will be examined. In table 1 the mean durations of perceived localisation of one disc in front for each pattern are reported. A two-way ANOVA for repeated measures, with contour type and disc size as factors, showed that contour type is the only significant factor in determining the order of overlapping ($F_{1,23} = 6.18$, $p < 0.02$). In particular, in the case of pattern 2 the phenomenal disc with fuzzy contour is perceived to slide on top of the disc with sharp contour for most of the time, as can be seen by considering the mean duration of perceived localisation (see table 1). In contrast, in the case of pattern 1, the two perceived discs alternate in the foreground continuously and there is no significant difference in the mean duration of localisation. It must also be noted that, in the case of pattern 4, the disc with fuzzy contour, which is smaller than the one with sharp contour, remains in the foreground for most of the time and the difference between the mean localisation duration is significant ($t_5 = 2.152$, $p < 0.04$). However, in the case of pattern 3, even though the mean localisation durations appear to be different, the t-test has shown that such difference is not significant: ($t_5 = 1.53$, ns).

These results seem to corroborate the hypothesis put forward in section 1. The presence of fuzzy contours, by changing the appearance of the one of the discs, makes the direction of completion more stable; furthermore, the disc with fuzzy contour appears most frequently in front and this implies that kinetic fuzzy illusory contours are more easily formed than sharp ones.

The results may be relevant also for static spontaneously splitting figures (Koffka 1935; Kanizsa 1955; Petter 1956; Shipley and Kellman 1992). Consider figure 4, first proposed by Kanisza (1955). This figure—a black homogenous surface as a distal stimulus—may segregate into two surfaces, a square and a cross. Consider the case of a square in front of the cross. In this case we have some normal contours, illusory contours to complete the square in front, and amodal contours to complete the cross behind. The so-called Petter laws (Petter 1956) state that the order of stratification depends on the ratio between the lengths of the amodal and illusory contours that the visual system has to construct. That is, the figure for which the visual system has to complete a shorter illusory contour stays in front, because constructing an amodal contour is easier than constructing a modal one. As remarked by Shipley and Kellman (1992), these constraints could specify the order of stratification in the absence of depth information. This explanation seems to hold in case of sharp

Table 1. Mean duration in s (with standard error in parentheses) of the perceived localisation of one phenomenal disc in the foreground: D1 (sharp), D2 (sharp) for pattern 1; D3 (fuzzy), D4 (sharp) for pattern 2; D5 (large sharp), D6 (small sharp) for pattern 3; D7 (large sharp), D8 (small fuzzy) for pattern 4; see figures 2 and 3.

Pattern 1	Pattern 2	Pattern 3	Pattern 4
D1 57.42 (1.18)	D3 89.71 (10.98)	D5 47.74 (8.02)	D7 42.60 (8.10)
D2 62.65 (1.79)	D4 31.30 (8.71)	D6 72.28 (8.04)	D8 77.45 (8.12)

contours. In contrast, when fuzzy illusory contours are present, sometimes the cross comes in front, as informally observed by Kanisza and by ourselves. The Petter laws need to be somewhat amended and a more complex explanation must be invoked; for instance, it has been hypothesised (Kanizsa et al 1982) that less energy is required for the formation of a fuzzy illusory contour than of a sharp one.

In table 2 are shown the mean perceived height of the 3-D object (truncated cone) for each pattern and for vertical and horizontal orientations. A three-way ANOVA for repeated measures with contour type, size, and orientation as factors demonstrates that all factors are statistically significant to modify the apparent height (for contour type $F_{1,47} = 4.09$, $p < 0.05$; for size $F_{1,47} = 4.25$, $p < 0.05$; and for orientation $F_{1,47} = 4.6$, $p < 0.04$).

A detailed analysis of the data indicates that (a) the apparent height of the truncated cone is greater when determined along the vertical axis; (b) the height is greater for patterns with fuzzy contours; and (c) the height is greater for patterns 1 and 2, that is, for patterns that split into discs of equal size.

In general these results seem to be relevant for the different interpretations of the stereokinetic effect. The dependence of the apparent height on orientation make questionable the explanations which derive the apparent height from some process that minimises either the distances (Musatti 1955) or the linear velocities (Zanforlin and Vallortigara 1988) of the points constituting the rotating figure. In particular, the model proposed by Zanforlin and coworkers explains the formation of a 3-D percept from a two-dimensional pattern without invoking the rigidity hypothesis. When applied to the patterns used in the present experiment, the model predicts that the apparent height is a function of the radii of the discs and of the distance between the centre of gravity of the pattern and centre of the discs. Thus, the prediction of the model seems to be partially confirmed by our findings showing that the apparent

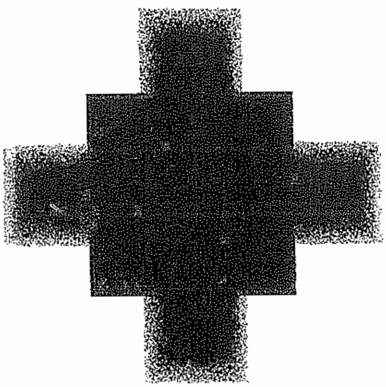


Figure 4. Static spontaneously segregating figure from Kanizsa 1955; see text for a description of the phenomenon.

Table 2. Mean height in cm (with standard error in parentheses) of the perceived 3-D object for patterns 1, 2, 3, and 4, in the vertical and horizontal orientation.

Pattern	Vertical	Horizontal
1	6.81 (1.24)	5.58 (1.48)
2	8.79 (1.17)	7.29 (1.52)
3	6.03 (0.41)	3.94 (0.42)
4	6.96 (0.77)	5.20 (0.82)

height is greater in the case of patterns 1 and 2, but this model cannot predict the dependence on orientation of the apparent height of the 3-D percept. In fact, the linear velocity remained invariate during our experiment. Furthermore, the model of Zanforlin and coworkers implies the choice by the observer of two reference frames. In our case the observer should choose as the origin of such reference frames the centre of gravity and the centre of one of the discs; it is clear that such a choice would be rather difficult because the 8-shaped figures do not provide any clue about such points. Last it must be noted that the type of contours affects the strength of the depth effect and this result cannot be explained by the Musatti or Zanforlin models. On the contrary, our results seem to support the hypothesis proposed by Proffit and coworkers (1992), according to which the apparent height is neither indeterminate nor completely specified by the motion, but must be derived by cues extraneous to the motion.

We propose here a tentative model of the perceived movement of our patterns. The model is based on the following simple assumptions: (a) the perceived, or reconstructed, motion must be consistent with the sensory input, that is, trajectories of the points of the pattern must agree, at every instant, with the instantaneous distribution of light intensity; (b) the principle of figural identity (the aperture problem) holds; (c) the decomposition of the 8-shaped pattern into two discs implies that each part has a definite relation with the other; this is to say that of the two discs resulting from the decomposition one must necessarily be superimposed on the other and, hence, the depth effect is due to a 3-D interpretation of the resulting pattern.

The 8-shaped pattern, E, can be considered as being formed of two discs partially superimposed, or, more formally, as the symmetric difference of two discs D and D′ (see figure 5). Let O be the centre of rotation and let C and C′ be the centres of D and D′, respectively. Consider a system of coordinates (X, Y, Z) with origin in O, the Z-axis orthogonal to the frontoparallel plane, and the Y-axis the vertical axis on the plane.

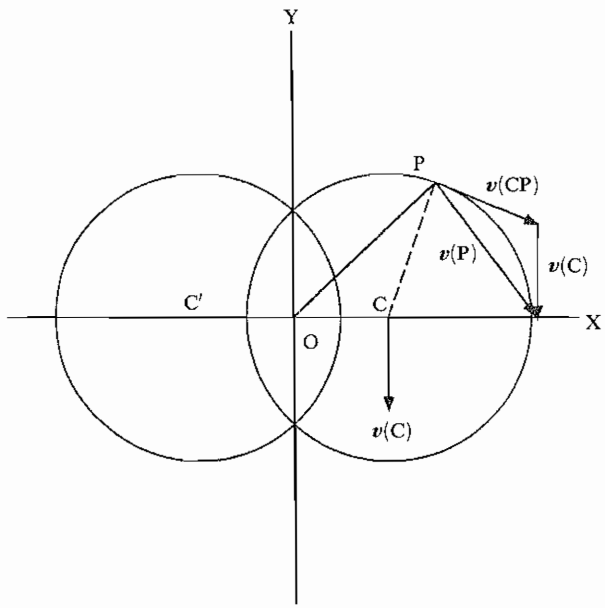


Figure 5. O is the rotation centre of the figure; C and C′ are the phenomenal centre of the discs; P is a generic point in the figure; $\boldsymbol{v}$(P) is the velocity vector of point P; $\boldsymbol{v}$(C) is the velocity vector of the centre of the phenomenal disc with respect to the rotation centre O; and $\boldsymbol{v}$(CP) is the velocity vector of point P with respect to the point C. See text for the vectorial analysis.

The position of each point P of E is defined by a vector $\vec{OP}$ in the plane XY, which can be written as $\vec{OP} = \vec{OC} + \vec{CP}$. Let P belong to the half plane $H(x > 0)$, and suppose that the 8-shaped figure makes a clockwise rotation.

The motion of P can be seen as the composition of two motions: the motion of C with respect to the origin, and the motion of P with respect to C. Then the velocity of P can be written as $\boldsymbol{v} = \boldsymbol{v}(C) + \boldsymbol{v}(CP)$, where $\boldsymbol{v}(C)$ is the velocity of C with respect to O, and $\boldsymbol{v}(CP)$ is the velocity of P with respect to C (see figure 5). The motion of P with respect to C takes points of the same light intensity one onto the other and then cannot be perceived [see assumption (b)], whereas the motion of C with respect to O takes points of different light intensity one onto the other. Then the perceived trajectory is that of a disc whose points move with the same velocity vector $\boldsymbol{v}(C)$ (same modulus, orientation, and direction), which is always orthogonal to the main axis of the 8-shaped pattern and defines a uniform circular motion with centre O. It must be noted that the principle of stability of orientation, invoked by Musatti (1955) and Wallach and Centrella (1990) to explain this kind of apparent motion, is a consequence of our hypothesis. A similar line of reasoning shows that for points belonging to the half plane $H(x < 0)$ the perceived motion is that of a disc whose velocity is $\boldsymbol{v}(C') = -\boldsymbol{v}(C)$. Thus the decomposition of the pattern E is a consequence of the fact that points belonging to different parts of E move with opposite apparent velocities; however, it remains to be explained why the illusory contour which is formed has a circular shape. There is convincing evidence in the literature (Sumi 1989) that factors such as good continuation and closure play a fundamental role in determining the shape of kinetic contours. Such factors could be at work also in the present case to determine the circular shape of the illusory contour.

It could be argued that there is no a priori reason why the motion should be decomposed in the way described above; indeed, given any point Q of the figure, it is always possible to write $\boldsymbol{v} = \boldsymbol{v}(Q) + \boldsymbol{v}(QP)$. However, such a decomposition would imply a perceived motion around the point Q, and that would violate the stability of orientation.

As a conclusion we propose some tentative explanations of our other experimental findings. First let us consider the dependence on orientation of the apparent height: it can be suggested that the judgment is biased by the vertical–horizontal illusion (Coren and Girgus 1978), which brings about an overestimation of the vertical extent. Finally, the influence of fuzzy contours on the perceived height can be explained as follows: even in the static condition the fuzziness appears to produce a 3-D effect, as remarked by Metzger (1930) in the Ganzfeld experience, and by Kanizsa (1979) in the case of transformation of surface colour into film colour; it is natural to suppose that such an effect remains also in the dynamic condition.

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