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No within-object advantage for detection of rotation

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Abstract

It is known that in a detection task the type of rigid transformation to be detected (reflection vs. translation) interacts with the type of display (closed vs. open contours). The advantage for closed contours found with reflection is believed to be a general within-object advantage, whilst the advantage for open contours found with translation is an exception, described as a lock-and-key process (Acta Psychol. 95 (1997) 119). We tested rotation, using a reaction time paradigm, and found the same result as for translation. Moreover, we found that the critical factor is not the number of objects present, rather it is whether the comparison is made across a surface or across an aperture between surfaces. Post-experiment interviews did not confirm any difference for observers who reported using a conscious lock-and-key mental transformation. We speculate that seeing a translation or a rotation across a closed figure is difficult because the closure of the figure emphasises the mismatch of the contour polarities on the two sides of the figure. That is, there may be a closed object advantage for detecting a difference in polarity which interferes with the task of detecting a regularity in shape. Evidence from the analysis of foil rejection trials supports such a speculation. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

When two patterns are related by a rigid transformation their metric structure is preserved. In the two-dimensional Euclidian space such transformations have familiar names: reflection, translation, and rotation (and glide reflection when a reflection is combined with a translation). However, to the human visual system such transformations may be more or less salient (e.g., Kahn & Foster, 1986; Mach, 1886). This issue is generally discussed in the context of perception of symmetry because such transformations can define symmetric patterns, namely patterns with self-similarity (for a review see Wagemans, 1995, 1997 or Tyler, 1996). [1] In this paper we use pairs of line contours that are related to each other by a rigid rotation, but we add a context to the display so that the contours are open or closed in various ways. We are interested in the effect of context because closing the contours differently changes the coding of convexity and concavity. Even though convexity and concavity information is irrelevant for the task of detecting a rotation of the contours, we found in other experiments that such information is processed obligatorily by the visual system (Bertamini, 2001, see also Driver & Baylis, 1996). In this paper we explore how the role of polarity may help us understand the fact that closure hinders detection of regularity in the case of translation and rotation.

2. One-object versus two-objects

It is known that performance in detecting the presence of a rigid transformation between two contours is affected by perceptual organisation and grouping. In reac-

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[1] There are difficulties with the terminology which have been pointed out before (e.g., Palmer, 1999; Wagemans, 1995, 1999a). Symmetry is often introduced as a transformation, but for such transformation to be a symmetry it needs to conform to the definition of a group. In particular such transformation should always generate elements of the group, i.e. a group should be closed (Weyl (1952), calls this an automorphism). In this paper we concentrate on the transformations themselves, consistently with how the effect of closure on translation has been studied (Baylis & Driver, 1995; Bertamini, Friedenberg, & Kubovy, 1997). This allows us to deal with translation and rotation in finite stimuli. However, it should be noted that symmetry can be created with rotations by an angle which when repeated fits into 360° without remainder, and these point patterns have been studied for instance by Royer (1981) and by Palmer and Hemenway (1978). Rotational symmetry is quite interesting in its own right. For instance, Weyl (1952) has suggested that it is the presence of rotation without reflection that led some ancient civilisations to ascribe magic power to the triquetrum and to the swastika. Historically, it was Leonardo da Vinci who came to the correct conclusion that for a finite object there are two central symmetry groups: pure rotations by an angle which when repeated fits into 360° without remainder, and rotations combined with reflections of a given motif, such as the petals of a geranium (Weyl, 1952). However, as stated before, in this paper we will confine ourselves to pure rotations as rigid transformations by arbitrary angles.

Another problem with the terminology is the fact that reflection around one axis (*pq*) is also called bilateral symmetry or mirror symmetry, and sometimes it is simply called symmetry. Translation (*pp*) is sometimes also called repetition (e.g., Baylis & Driver, 2001; Corballis & Roldan, 1974; Van der Helm & Leeuwenberg, 1996). We use the terms reflection, translation, and rotation for the three types of rigid transformations. Because they are rigid transformations they have in common a one-to-one match of every single point on the two contours. This perfect correlation is what observers were asked to detect, and the lines used to create closed regions are by definition an added context.

tion time experiments, there is an advantage for detecting the presence of a reflection of two contours when the contours are closed to form a single object, as opposed to contours belonging to separate objects. The same effect is observed when the figure-ground organisation is determined not by the closure of the lines, but by the instructions to the observer (Baylis & Driver, 1993) and perhaps even by the distance itself between the two halves (Corballis & Roldan, 1974). However, the opposite effect, an advantage for separate objects, is present for detection of a translation of the contours (Baylis, 1994; Baylis & Driver, 1993, 1995; Bertamini & Friedenberg, 2000; Bertamini et al., 1997; Corballis & Roldan, 1974).

This is important for a full understanding of the effects of grouping on detection of regularity (see also Locher and Wagemans (1993), for the effects of grouping of discrete elements like lines and dots). If comparisons are faster within an object because of an attentional cost, we would expect this to be true for any type of regularity, indeed for any type of processing of contour information. This within-object advantage is consistent with predictions based on object-based attention (Duncan, 1984; see also Behrmann, Zemel, & Mozer, 1998). Moreover, computational considerations about hierarchical coding of position lead to the same predictions: Relative positions of elements are first coded within a group, and only a second iteration gives the relative position between groups (Watt, 1988; Watt & Morgan, 1985).

The best explanation of the finding of the opposite effect (a between-objects advantage) for detection of translation is a different process which has been called "lock-and-key" or "jigsaw matching", but is not as well understood (Baylis & Driver, 1995; Bertamini et al., 1997). Bertamini et al. (1997) found that the lock-and-key process is not a simple sliding in the plane of the two regions, in the sense that it depends on whether the parts appear to be related to each other, as opposed to being perceived as independent objects. This was found by manipulating the prägnanz of the parts (Bertamini et al., 1997). However, this was only a first step in the attempt to understand this process that seems to overcome the within-object advantage discussed above. In this paper we looked at conscious awareness of a lock-and-key strategy by interviewing all the participants in Experiment 2.

3. The role of contour polarity

With respect to the difference between reflection and translation, one important factor is contour polarity. We use this term to refer to the sign of the curvature of a contour, or in other words the presence of convexities and concavities (therefore contour polarity has no relation to contrast polarity). According to Baylis and Driver (2001) an efficient comparison of contours can only take place when polarity is consistent (i.e., a convexity on one contour corresponds to a convexity on the other). This does explain to some extent the well known fact that reflection in an object is detected faster than translation (the original observation was in Mach (1886)). However, Baylis and Driver (2001) also found that efficient processing requires closure in the sense that the comparison must be within an object.

Bertamini (2001) has also demonstrated the importance of contour polarity in perception of shape. He found that for simple vertices, positional information is processed more quickly when they are perceived as convex (see also Gibson, 1994). Bertamini (2001) suggested that the reason is that polarity is critical for how we see shapes, in that convex regions are segmented as parts, whilst concave regions are simply boundaries between parts (Hoffman & Richards, 1984) and therefore a position is assigned to parts with priority over the boundaries between parts.

However, it is important to keep in mind that the advantage for a between-objects comparison for detection of translation cannot be explained by a difference in polarity. It is true that if polarity is forced to match, for instance using two congruent closed objects side by side, the task becomes easier (Baylis & Driver, 1995), but it becomes easier even if the two-objects face each other which is what we also call a lock-and-key configuration. In the case of translation the polarity of the contours does not match whether the contours are closed to form a single object or separate objects in a lock-and-key configuration (Baylis & Driver, 1995; Bertamini et al., 1997). Nevertheless, we will return later to polarity to discuss how it might indirectly explain the lack of a within-object advantage for detection of translation.

4. Different types of rigid transformations

The literature reviewed has concentrated on reflection and translation. The studies reported in this paper test a third type of rigid transformation: rotation. Rotation rigidly maps one contour onto another and in this sense is no different from reflection and translation. Detection of rotation has been explored before and in general has been found to be less salient than reflection (e.g., Hulleman & Boselie, 1999; Kahn & Foster, 1981, 1986; Palmer & Hemenway, 1978; Royer, 1981; Wagemans, Van Gool, Swinnen, & Van Horebeek, 1993), but the interaction of this type of regularity with closure is not known. If the closure disadvantage for translation is due to the fact that it is easier to compare translated contours that face each other ("lock and key"), it should apply to contours that are rotated away from each other, especially if the centre of rotation is clearly defined in the image.

The interaction between closure (closed vs. open) and type of transformation (reflection vs. translation) also suggests that reflection may play a special role in perceptual grouping, i.e., a synergy with the role of closure. It is possible that reflection is a non-accidental property of the stimulus that the system employs not only to recover 3D structure (Wagemans, 1993) and represent a shape (Marr & Nishihara, 1978) but also to perform an early image segmentation or find "regions of interest" (Bonneh, Reisfeld, & Yeshurun, 1996). For this reason, detecting reflection may be facilitated by grouping factors, such as closure, that are consistent with that segmentation. By consistent we mean that they apply to the same region of the scene and enhance the probability that that region is seen as an object. We expect consistent grouping factors to facilitate processing.

However, a within-object advantage is a general phenomenon at least in the sense that it has been found in cases when the judgement is a comparison of contour information that is not about rigid transformations (Baylis & Driver, 1993; Hulleman & Boselie, 1997). For instance, Baylis and Driver (1993) used simple lines that had one sharp angle (creating a vertex). The vertical position of the vertex was to be compared between two such lines, and observers had to decide which vertex was higher. The central region of such a display would therefore look like a slightly irregular hourglass. By manipulating the closure of the lines, Baylis and Driver (1993) found a within-object advantage. In a modified version of the same experiment Baylis (1994) used lines arranged as chevrons, and replicated the finding. Note that this arrangement is very similar to a task where translated contours are used, for instance Experiment 4 in Baylis and Driver (1995) which tested detection of translation. The chevrons are slightly irregular and the task is to say whether the higher vertex is on the right or on the left; nevertheless the result is the opposite: with the chevrons there is a within-object advantage, whereas with translated contours there is a between-object advantage. Prima facie this suggests that more than one factor may be at play.

The lack of a consistent pattern for the effect of closure makes the present investigation of rotation particularly important. We predict that detection of rotation will replicate the finding for detection of translation. Contrary to previous discussions in the literature we suggest that it is not sufficient to talk of a lock-and-key process to explain the advantage for the between-objects condition, rather there may be a within-object cost specifically for detection of rotation and translation when the contours are closed. We will discuss this in light of the special role that the polarity of the contours may play when the shape of such contours is compared.

5. Experiment 1: Effects of closure on detection of rotation

We investigated the effect of closure of contours in a speeded response task. Observers were asked to compare two contours created with black lines on a computer monitor, and press one of two keys depending on whether the contours were related by a rotation or not. The basic effect of closure has already been reported: for reflection, comparison of closed contours is faster than contours that are not closed, or more precisely contours that are closed to form two separate objects, whereas for translation comparison of closed contours is slower (Baylis & Driver, 1995; Bertamini & Friedenberg, 2000; Bertamini et al., 1997).

To generate the stimuli, we rotated the contours around a reference point and then closed the lines with chords and arcs. We created the closed and open conditions using three different configurations. (a) To try and match as closely as possible the stimuli used to study reflection and translation we created and compared closed contours forming one-object versus two-objects. By definition we refer to completely enclosed regions as objects. This configuration (“objectness”) is illustrated in the left panel of Fig. 1. (b) Because closure may be important independently of number of objects, in the second type of configuration we closed the contours so that there was always one-object. This configuration (“pacman”) is illustrated in the middle panel of Fig. 1. (c) Finally, we wanted to use a configuration in which the rotation of the contours was not around one extremity of the contour but rather around the

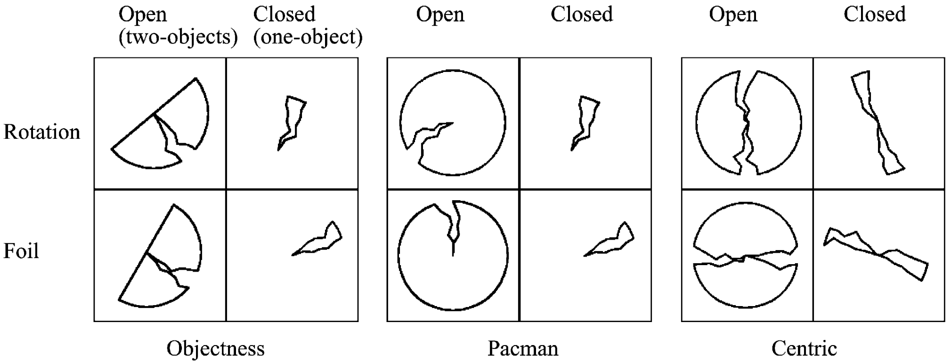


Fig. 1. Examples of stimuli used in Experiment 1. The shape of the contours was generated according to a constrained random walk algorithm in each trial. Moreover, the orientation around the centre of the display was randomised in each trial. The angle of rotation was either 20°, 40° or 60°, but only the 20° rotation is shown in the figure.

centre. This configuration ("centric") is illustrated in the right panel of Fig. 1. Note that in the Pacman stimuli only one closed object is present in all conditions, whereas in the Centric stimuli two-objects are present.

5.1. Method

5.1.1. Participants

Twenty-seven Staffordshire University students participated (nine for each configuration). They were naïve with respect to the problem and the hypotheses until after the data were collected.

5.1.2. Design

A 3 configurations (objectness, pacman and centric) ×2 closure (closed and open) ×3 angle of rotation (20°, 40° and 60°) mixed design was used. The three configurations were tested with different participants whilst all other factors were within-subject.

5.1.3. Stimuli and procedure

Examples of the stimuli are illustrated in Fig. 1. The centre of rotation (origin) was always at the centre of the screen but the stimulus orientation relative to the origin was randomised in each trial, and the examples in Fig. 1 are some of the possible orientations. The stimuli were presented as anti-aliased black lines on a white monitor (resolution 1024 × 768), controlled by a PowerPC Macintosh computer. The contours to be compared were generated by a modified random walk with six steps (12 for the centric configuration). In each step, the distance away from the origin was fixed (10 pixels), while the orthogonal offset was chosen randomly (12 pixels max.). To limit the chance of overlapping contours the offset for the three inner steps (near the origin) were half as large as for the outside steps. This did not mathematically exclude some occasional overlap for the 20° rotation foil stimuli used in the experiment. In the target trials, the second contour was generated by rotation around the origin. The maximum extent of the stimulus (diameter of an enclosing circle) was 120 pixels and corresponded approximately to 2° of visual angle.

Note that because of the random nature of the walk some contours may be more jagged than others. The stimuli in the foil trials were generated by the same algorithm (random walk), except that the two contours were generated independently, therefore the only difference between target and foil trials was the relationship between the two contours.

Each observer was seated in a dimly illuminated room at a distance of approximately 57 cm from the monitor. They were given instructions and shown examples of the stimuli before the experiment started. Once started, 24 trials formed a practice phase, and after this if the observer felt confident the experiment started, otherwise more practice was provided. Each participant responded to 720 trials in rapid succession, but every 120 trials a block ended and the observer was allowed time to rest. The start of subsequent blocks was self-paced. An acoustic feedback informed the participant of any mistake made during the experiment.

Regarding the factor closure, note that the labels should always be interpreted with respect to the region between the contours to be compared. For instance, in the case of the Centric condition there are always two closed figures, but the rotated contours are separated by an open space in the open condition and by a closed surface in the closed condition.

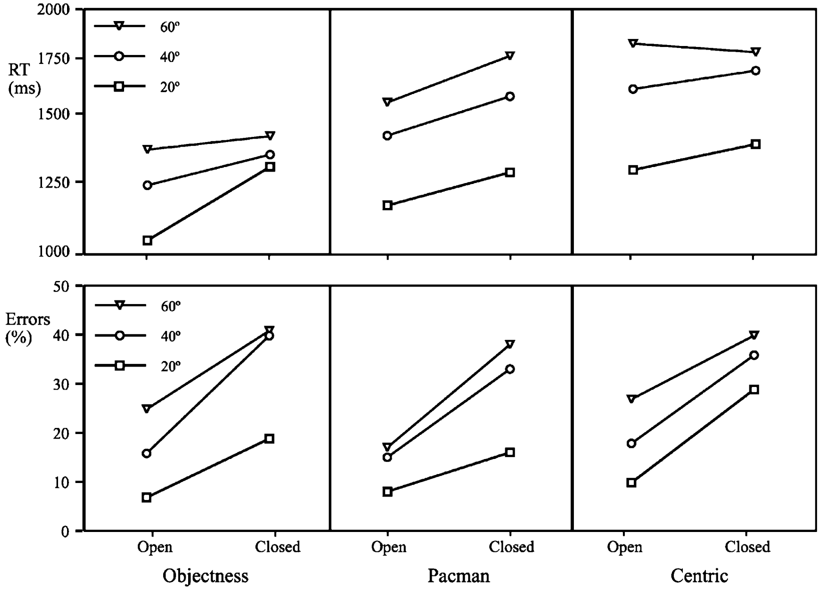
5.2. Results and discussion

The following steps were taken in this as well as in all the analyses for subsequent experiments. Responses that took longer than 6000 ms were discarded. The response time in ms (RT) was logarithmically transformed for two reasons; first, to normalise the distribution and meet the assumptions of ANOVA; second, because there are some theoretical reasons to expect lognormal RT distributions (Ulrich & Miller, 1993). Target and foil data were analysed separately.

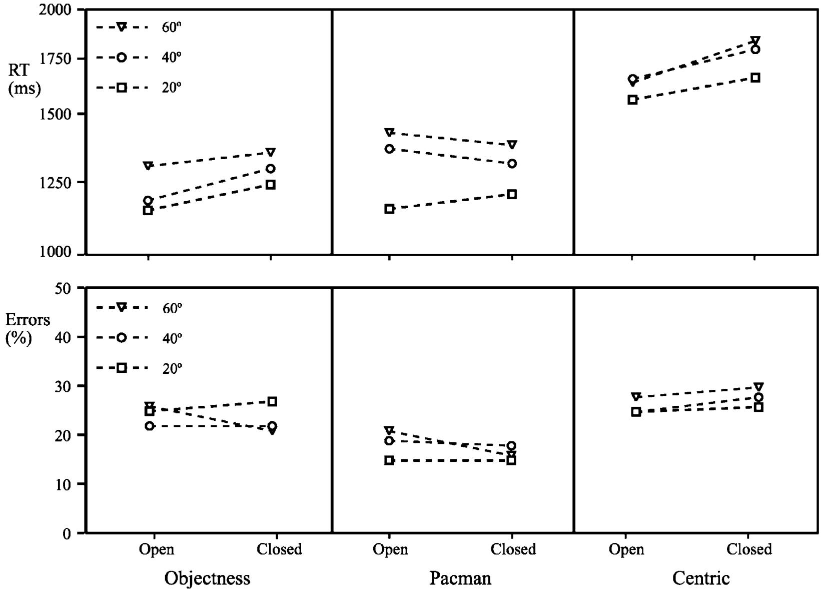
5.2.1. Target detection

We ran a mixed ANOVA on transformed RT with configuration, closure, and angle of rotation as factors (a $3 \times 2 \times 3$ design). The analysis found a main effect for closure ($F(1,24) = 8.56$, $p = 0.007$), a significant effect of angle of rotation ($F(2,48) = 103.61$, $p < 0.001$), and a significant interaction between angle of rotation and configuration ($F(4,48) = 3.64$, $p = 0.011$). No other effect or interaction was significant. The means can be seen in the graphs of Fig. 2.

The analysis of the errors showed the presence of a high level of misses, i.e. rotated contours that were judged to be unrelated. Fig. 2 shows that the overall pattern of errors is consistent with the performance measured by response time. An ANOVA on percent correct scores confirmed the significant effect of closure ($F(1,24) = 21.79$, $p < 0.001$) and angle of rotation ($F(2,48) = 40.45$, $p < 0.001$). In



Target data



Foil data

Fig. 2. Data from Experiment 1. Mean RT (above) and errors (below) are plotted separately for the different configurations and also for target data (right) and foil data (left). Note that RTs were analysed after a logarithmic transformation and the graphs therefore have a log scale. These arithmetic means correspond to geometric means of untransformed RT. Because targets and foils are shown separately, the errors are misses and false alarms, respectively.

addition, there were significant interactions between angle of rotation and closure ($F(2,48) = 3.64$, $p = 0.034$) and between angle, closure and configuration ($F(4,48) = 3.18$, $p = 0.021$). The two and three way interactions did not imply a change in direction of the effect of closure for different angles, nor a change in the order by difficulty from 20° to 60° for the angle of rotation for different configurations (see Fig. 2).

5.2.2. Foil rejection

The same design was used to analyse foil data. For RT there was an effect of angle ($F(2,48) = 32.07$, $p = 0.001$) and an interaction between angle and configuration ($F(4,48) = 2.91$, $p = 0.031$). With respect to errors there was no significant main effect nor interaction. Therefore, the effect of closure was only present for target data, whilst the effect of angle of rotation was more robust.

The pattern of the interactions should be understood by a close inspection of Fig. 2. For instance, in the target data the effects of angle of rotation may vary with configuration but they retain the basic pattern (especially for errors where the differences are quite large). The pattern for the Centric condition will be considered in more detail below. Also in the target data the interaction between angle of rotation and closure for errors seems of no great consequence as it originates from a lack of parallelism but not a change in the direction of the effect.

6. Comparison of the three configurations

In Experiment 1 we used three different configurations labelled objectness, pacman and centric. They are all manipulations of the closure of the contours, but have different strengths and weaknesses; therefore, we review here what we can learn from each of them.

(a) *Objectness*: There was an advantage for the two-objects condition (open) but only in the target data. This suggests that detection of rotation and detection of translation are similar. An overall cost may be present for processing or comparing two-objects, but for translation and rotation over and above this cost there is another effect that makes the two-objects condition easier. This effect in the literature has been called a “lock-and-key” advantage (in the context of translation). However, Bertamini et al. (1997) found that this lock-and-key matching is not a simple mental sliding of one shape into another, and on the basis of Experiment 1 we can also say that it does not require parallelism of the contours. One limitation is that the two-objects stimuli may have contained in themselves a more clearly defined frame of reference for the rotation.

(b) *Pacman*: It is reasonable to assume a similar type of processing for both translation and rotation by the visual system. However, rotation gives us the opportunity to investigate the meaning of a “lock and key” process in new ways. What appeared to be a two-object advantage for translation may be a “gap” advantage. In the Pacman condition the arc was completed to form only one-object in both open and closed conditions. Therefore it was not possible to perform a mental translation of two separate objects to match the two contours. Moreover, strictly speaking the difference cannot be due to the number of objects, as only one-object was present in both conditions (although it was bigger in the open condition).

(c) *Centric*: In this condition the rotation was around the centre of the contour rather than one extremity. As can be seen in Fig. 1 (Centric) both open and closed conditions have two-objects and the difference is whether the inside or the outside distance between the lines is closed by an arc. When the inside (shorter) distance is closed we call this the closed condition (here the comparison is across a surface), in the other case we use the term open condition (here the comparison is across a gap). Note that, although for RT data there was no interaction between configuration and closure, the direction of the effect is different in the RT data in the case of the Centric condition with a 60° angle; however, the effect was strong in the pattern of errors (approximately a 20% difference). We note but will not place much emphasis on this trade-off, and we rely on the massive difference in errors to talk about an advantage for the open condition.

In summary, all three conditions of Experiment 1 confirmed an advantage for the open condition, i.e. an advantage for comparing contours across an aperture (“gap”) as opposed to across a surface. The effect of angle of rotation was also significant, and although this interacted with the type of configuration, the graphs show a consistent order from 20° to 60°: larger angles made the task harder (and reduced the effect of closure) consistently with the literature (e.g., Kahn & Foster, 1981).

7. No within-object advantage and attention

The lack of a within-object advantage is interesting because it goes against the prediction based on attention (as well as hierarchical coding of position). That is, within-object judgements should always be easier because attention is object-based (Baylis & Driver, 1993; Duncan, 1984). Now we are finding that the effect is not dependent on number of objects, but rather the presence of an aperture, and perhaps objectness as such is not the critical variable. However, this new aperture advantage is still surprising. It seems reasonable to expect that tasks requiring attention should be affected by the size of the region to be attended to (although it is recognised that the focus of selectivity is not a simple question of visual angle, e.g. Broadbent (1982); Murphy & Eriksen (1987)). Looking at the stimuli in Fig. 1 it could be argued that, based on the size of the stimuli, the easier condition should be the closed one (especially for the Pacman stimuli). This is not the case, and moreover we found that the advantage for the open condition was only present for the target trials. Although we do not suggest that we should abandon the idea of a within-object advantage linked to attention, we will have to look somewhere else for an explanation of the gap advantage which overcomes the within-object advantage in our data. In particular we suggest that the present effect is more related to shape perception than attention (see Wagemans (1993) and Wagemans et al. (1993) for a similar argument on the need to link perception of symmetry and perception of shape in general).

8. Experiment 2: Conscious use of a lock-and-key strategy

Experiment 2 was similar to Experiment 1 except for the following changes: (a) A new baseline condition was used to compare open and closed stimuli against isolated contours. We expect performance in the new baseline condition to be intermediate between the open and closed conditions in the sense that this is an ambiguous stimulus. This control is also important because it could be argued that closing rotated contours breaks the symmetry in a way that is not true for reflection. More specifically, when two reflected contours are closed to form one-object the reflection applies to the context as well (the extra lines), but when two translated or rotated contours are closed, there is no context that is translated or rotated rigidly with those contours. (b) Four types of closure ("one-object", "two-objects", "pacman" plus the new "baseline") were interleaved. If the difference is as fundamental as we have previously argued, and not subject to the effect of different strategies, we predict the same results as found in Experiment 1 even though in the previous experiment the type of configuration was a between-subject variable. (c) After the experiment, participants were interviewed and asked whether they were conscious of adopting any specific strategy. In particular, we wanted to investigate the use of a "lock-and-key" strategy and to compare subjects who claimed to have used different strategies.

8.1. Method

Twenty-two University of Liverpool students took part in this experiment. They were naïve with respect to the problem and the hypotheses until after the data were collected. The design and procedure of Experiment 2 were similar to the design and procedure of Experiment 1. There were two within-subject factors: shape (baseline, one-object, two-objects, and pacman), and angle of rotation (20° and 40°). The overall orientation of the stimulus was a random factor as in Experiment 1, although now it could only assume one of two levels, above or below the origin (180° difference). Examples of the 40° rotation stimuli in the above orientation are given in Fig. 3.

8.2. Results and discussion

The analysis was similar to that of Experiment 1. We ran repeated-measure ANOVAs on log-transformed RT separately for target and foil data. The factors were shape and angle of rotation (a 4×2 design).

8.2.1. Target detection

There was a highly significant effect for angle, as in Experiment 1 ($F(1,21) = 108.77$, $p < 0.001$), a significant effect for shape ($F(3,21) = 29.65$, $p < 0.001$) but no significant interaction between the two. Unlike Experiment 1, shape is now a variable with four levels. To compare the four, we plotted within-subject standard errors in Fig. 3 (Loftus & Masson, 1994) and performed post-hoc tests. It is evident from the graphs that participants took longer to respond to the one-object shape than to any of the other shapes, and this was supported by a Scheffé post-hoc test which

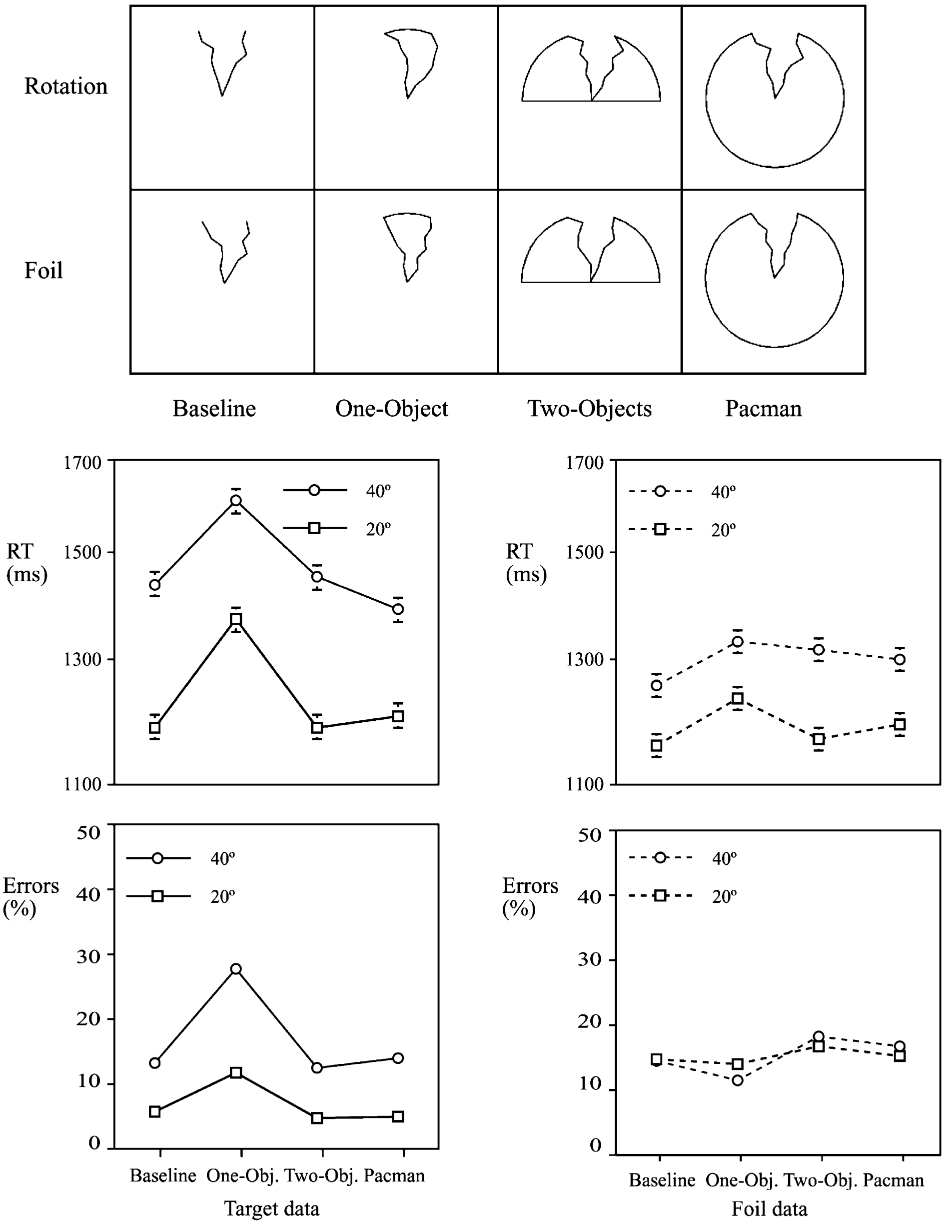


Fig. 3. Top: Examples of stimuli used in Experiment 2. The shape of the contours was generated according to a constrained random walk algorithm in each trial. Moreover, the orientation was either above or below the centre, but only examples above the centre are shown. The angle of rotation was either 20° or 40°, but only the 40° rotation is shown. Bottom: Data from Experiment 2. Mean RT on a log scale and errors are plotted, and for the RT values the error bars are within-subject standard errors. Data from the target trials and the foil trials were analysed and plotted separately, therefore the errors are misses and false alarms, respectively.

found that the mean reaction time to one-object stimuli was significantly different from the mean reaction time to all the other shapes (all p's < 0.001). Additionally, people were significantly faster when the angle of rotation was smaller (20° as opposed to a 40° rotation).

The ANOVA on percent errors confirmed the effect of angle ($F(1,21) = 53.55$, $p < 0.001$) and shape ($F(3,21) = 28.19$, $p < 0.001$) and the interaction was also significant ($F(3,21) = 8.29$, $p < 0.001$). The graph in Fig. 3 shows that the pattern is consistent with the reaction time pattern: People were slowest on the one-object shape and made more errors. The interaction seems to be simply due to larger differences in the 40° condition. Although the level of errors was lower than in Experiment 1, it was still quite high with a peak for one-object rotated stimuli.

8.2.2. Foil rejection

The analysis on RT for the foil data revealed a significant effect of angle of rotation ($F(1,21) = 51.24$, $p < 0.001$), a significant effect for shape ($F(3,21) = 5.07$, $p = 0.003$) and no interaction. The same analysis on percent errors confirmed an effect of shape ($F(3,21) = 6.34$, $p < 0.001$). However, comparing the effect of shape for RT and errors in the foil data reveals some inconsistencies. In general, it is also clear from Fig. 3 that the differences in the target data are larger than the differences in the foil data, consistently with the results of Experiment 1.

In summary, Experiment 2 confirmed the advantage for comparing rotated contours across an aperture, as opposed to a surface, for target trials (a difference ranging between 152 and 208 ms). The large number of misses in particular is similar to what was observed in Experiment 1. Experiment 2 used a within-subject design with 22 participants, as opposed to nine in each group in Experiment 1. Thanks to the greater power of the design the differences are clearer and perhaps for this reason a significant effect of shape was found also in the foil data. However, keeping in mind this difference in power, the results are remarkably consistent.

A new baseline condition was introduced in this experiment. These baseline stimuli were found to be easier than the one-object stimuli, suggesting that there is a one-object cost, rather than an advantage for the two-objects and pacman conditions. This may support the idea of a "lock-and-key" strategy in which participants mentally rotate one part of the display to match the other, because this strategy could be available also for the baseline stimuli. However, this hypothesis does not explain why the effect is stronger in the target data. To further test this possibility we now turn to the data collected by interviewing the participants at the end of the experiment.

9. Interview data

We interviewed all the participants in Experiment 2 to see what kind of explicit strategy they had adopted. In particular we were interested in any mental transformation strategy in which one part of the configuration is made to fit into the other (as in a jigsaw puzzle). We found that 13 out of 22 participants mentioned such strategy without any prompting. When the experimenter suggested the strategy as a possibility, seven more participants claimed that they made some use of it. Using the same steps detailed in the method section earlier, we ran a mixed ANOVA with shape, angle and strategy as factors. Target and foil data were pooled in this analysis. The new strategy factor had two levels (present or absent), this factor compared the 13 participants who claimed to have used a jigsaw strategy without prompting against all the others. Strategy was not significant ($F(1,20) = 0.15$) nor did it interact with any other factor. This was also true in a second mixed ANOVA (for strategy: $F(1,20) = 0.01$) which tested percent errors instead of reaction time as the dependent variable.

During the interview we also asked participants to estimate how often they thought that they had used the strategy during the experiment. The estimates varied between 0% and 100% but interestingly even some of the participants who claimed to have used the strategy without prompting reported values as low as 25%. Therefore we used a new classification based on the usage. We compared the participants who claimed to have used the strategy more than 50% of the time (10 out of 22) against all the others. Again, mixed ANOVAs on reaction time and on percent errors did not confirm any effect of strategy ($F(1,20) = 1.01$; $F(1,20) = 0.63$ respectively) or interaction of strategy with any other factor. We conclude that although introspectively people may feel that the stimuli slide into each other as jigsaw pieces, performance was not affected by the strength of such a feeling or the conscious use of such a strategy. As before, we suggest that the findings need to be explained by something more basic about how shapes are perceived and represented.

10. Experiments 3a and 3b: Different types of foil

We hinted in the introduction and the discussion of Experiment 2 that one way to explain the between-objects advantage is to hypothesise a within-object cost. Moreover, this within-object cost should be specific to the target stimuli. But why should it be hard to detect translation and rotation within an object, or more precisely when the contours to be compared are connected to form a surface (as opposed to a gap)? A change in polarity is not an explanation because both a surface and a gap would create a mismatch of the polarity between the two contours. Looking at the stimuli of Figs. 1 and 3 it is clear how any convexity on one side corresponds to a concavity on the other side (and vice versa).

A possible hypothesis however is that the importance of matching polarity within an object is so strong that a mismatch will always lead to the perception of an irregular shape. The task of detecting translation as well as rotation is a task in which observers are asked (and therefore should try) to detect a perfect (but negative) correlation between the two sides of an object. By that we mean that the convexities and concavities are as strongly related as in the case of reflection, but their correlation is negative: every convex feature on one side corresponds to a concave feature on the other. It is possible that the high efficiency in responding to a target with a positive correlation (reflection) has, as a by-product, the effect that it is hard to respond to a negative correlation when it is a target. To explore this possibility we designed Experiment 3 so that we could analyse which are the harder foils to reject: random ones or ones with a positive or negative polarity match.

There are two possible scenarios:

(1) When any rigid transformation is present, the regularity is extracted by the visual system using the same mechanism, although the presence of some regularities may be easier to compute than that of others. If so, although detection of reflection may be much faster, foil trials with any regularity should be harder to reject than foil trials without regularity. The function of transformations and symmetry for the human visual system is too broad a question for this paper to tackle. However, note that this scenario is consistent with some proposals in the literature about what symmetry is for. For instance, every rigid transformation could serve efficient encoding of information or "economy of representation" (e.g., Barlow & Reeves, 1979; see Tyler, 1996, for a review) or recovery of 3D information from a 2D projection (Kontsevich, 1996; Wagemans, 1993) as well as lead to "goodness" of the figure (e.g., Palmer, 1999). To some extent this first hypothesis is a straw man. We already know that there are important differences between the different regularities, and they are acknowledged in most of the literature (e.g., Wagemans, 1997). We use this scenario to clarify by contrast the following scenario.

(2) Reflection is extracted by a mechanism which is especially sensitive to structural information and in particular contour polarity within a closed figure (e.g., Baylis & Driver, 2001). Stimuli in which contour polarity is negatively correlated within a closed figure are salient only in that they signal the opposite of this regularity (i.e., the opposite of a reflection). Perhaps, even when such a negative correlation is the target, it is hard to perceive such figures as having any type of regularity. Although this may seem paradoxical, it is consistent with the high level of misses observed in Experiments 1 and 2 (even though an auditory feedback was always present) and with the presence of an effect only or mainly for target trials. We suggest that this is also consistent with the existing evidence that there is a separate encoding for acute and obtuse angles (Foster, 1980) and the evidence on the importance of polarity for shape perception (Bertamini, 2001; Hulleman & Boselie, 1997; Hulleman, te Winkel, & Boselie, 1998). If this hypothesis is correct, even when responding to reflected targets, foil trials with rotation should be easier to reject than those without any regularity.

Apart from the question of which foils are easier to reject, Experiment 3 will also test whether the effect of closure could be different for reflection and rotation (namely, a closed object advantage for the former and a disadvantage for the latter) within the same experiment. If our hypothesis is correct both effects should be detectable from within the same block of trials because they do not correspond to different strategies.

Other experiments in the literature have looked at different types of foils, or an exchange of target and foil (e.g., Corballis & Roldan, 1974; Royer, 1981). Royer (1981) for instance compared several symmetry groups when only one of them was the target. However, he used dots and lines within a square matrix which did not form closed objects, and when the target was varied the asymmetric condition was not included in the design. The stimuli most relevant with respect to our study were probably those used by Palmer and Hemenway (1978). They compared closed outlines with one, two, or four axes of reflection, near symmetry and rotational symmetry. The latter objects had two halves related to each other by a 180° rotation. Therefore, their stimuli were truly symmetric objects whilst what we use are objects created with rotated contours. Moreover, in Palmer and Hemenway's (1978) study the stimuli with two and four axes of reflection also had inherited rotational symmetry (although this was not a problem for the purposes of their study). Having noted all these differences, Palmer and Hemenway (1978) compared time to reject foils with near symmetry or rotational symmetry (the target was reflection) and they found that it took longer to reject rotational symmetry when orientation was unpredictable, but not when it was fixed.

10.1. Method

Twenty-two University of Liverpool students took part in Experiment 3a and 24 in Experiment 3b. They were naïve with respect to the problem and the hypotheses until after the data were collected. The design and procedure of Experiments 3a and 3b were similar to the design and procedure of Experiment 2. However, in Experiment 3 we only used 40° of rotation. Examples of the stimuli are given in Fig. 4.

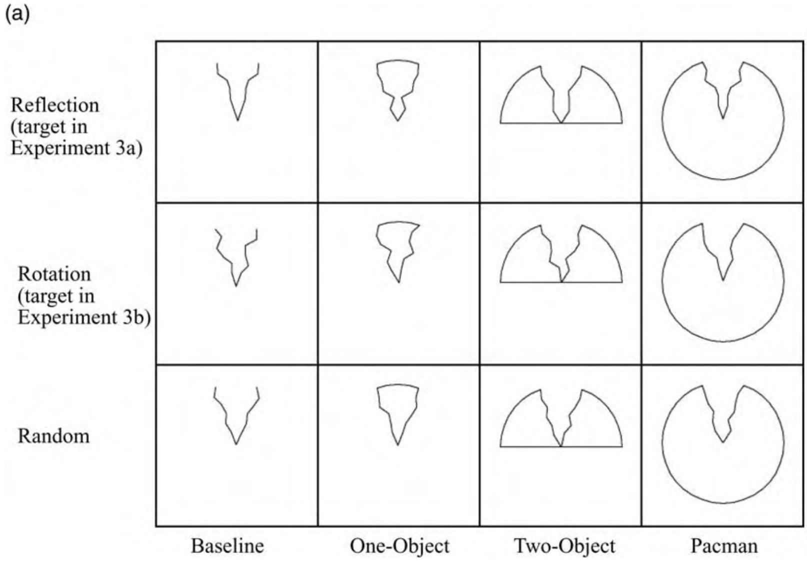


Fig. 4. (a) Examples of stimuli used in Experiment 3. The shape of the contours was generated according to a constrained random walk algorithm in each trial. Moreover, the orientation was either above or below the centre, but only examples above the centre are shown. The main difference between Experiments 3a and 3b was which type of stimulus was the target. (b) Data from Experiments 3a and 3b. Mean RT on a log scale and errors are plotted, and for the RT values the error bars are within-subject standard errors. Data from the target trials and the foil trials were analysed separately, but are plotted together to allow for a better comparison.

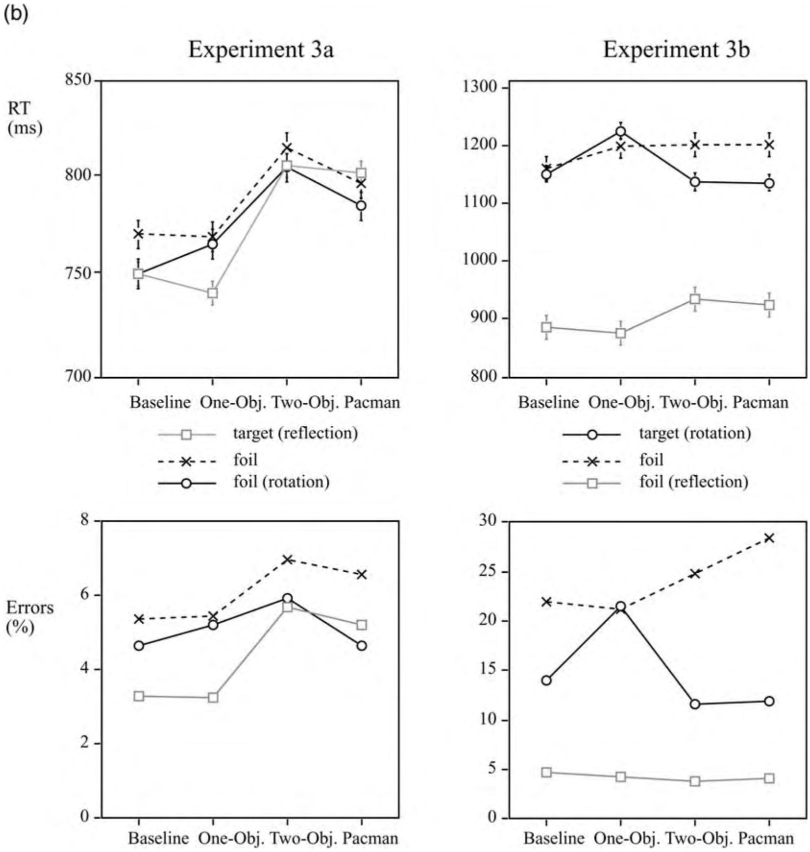


Fig. 4 (*continued*)

More importantly, in Experiment 3a participants were asked to detect reflection, which was present in half of the trials. Among the foils, half were random and half were rigidly rotated. Experiment 3b was exactly the same except that rotation was now the target and half of the foil trials were reflected.

The generation of the stimuli was similar to that of Experiment 2, and the same random walk algorithm was used for all contours. As before, the only difference between the three types of shapes (reflection, rotation, and random) was the relationship between the two contours (see Fig. 4).

10.2. Experiment 3a: Detection of reflection—results and discussion

The mean reaction time and errors are shown in Fig. 4 (left column). Although both target and foil data are presented in the same graph, the statistical analysis was done in two steps. The design of the ANOVAs always included the factors shape and orientation (3×2), but the analyses of the foil data also included foil type ($3 \times 2 \times 2$). Unlike Experiments 1 and 2 we can now compare two types offoils.

10.2.1. Target detection

We performed repeated measures ANOVAs on the log transformed RT and error percentages. For the reaction time data for targets, there was a significant effect of shape ($F(3,21) = 56.25$, $p < 0.001$), with people being significantly faster for the one-object and baseline shapes than for the two-objects and pacman shapes, replicating the well-known one-object advantage for detecting reflection. The same pattern was evident in the error data. Although errors were extremely low (all below 8%) there was still a significant effect of shape ($F(3,21) = 7.44$, $p < 0.001$).

10.2.2. Foil rejection

Half of the foil trials were rigidly rotated and half were random, therefore we analysed foil rejection performance in a second repeated measures ANOVA. The analysis showed that there were significant effects of shape ($F(3,21) = 33.65$, $p < 0.001$) and foil type ($F(1,21) = 9.59$, $p = 0.006$), but no interaction. People were again faster to reject baseline and one-object shapes, and they were faster to reject the regular foils (rotation) compared to the random foils (as confirmed by Scheffé post-hoc tests, all p's < 0.001). No significant effects were found in the errors but the level of errors was low (see Fig. 4).

Overall it can be observed that for target detection there is a one-object advantage when the target has reflected contours. Moreover, in the analysis of foil trials, there was a significant difference between the two types of foils used, with an advantage for rejecting rotated foils. This suggests that different types of transformations are not extracted by the same mechanism, or at least that they do not appear as related stimuli. Instead, the results support our speculation that, when compared to reflections, rotated contours are easier to reject than random contours. This is consistent with the idea that structural information and in particular contour polarity (i.e., convexity and concavity information) is important, because rotated contours always have opposite polarity, as opposed to uncorrelated polarity on the two sides.

Our finding that rotated stimuli are easier to reject than random stimuli is consistent with what was found by Palmer and Hemenway (1978) when the axis of orientation was kept fixed. Having said that, the differences in the stimuli pointed out before are too large to allow a closer comparison. Nevertheless, it is interesting to note that Palmer and Hemenway had stressed in their article the role of part matching across the main axis of elongation. In their words "Introspectively, at least, homologous parts on opposite sides give the impression of a possible axis of symmetry along the diameter connecting them [..] or perpendicular to that diameter" (Palmer & Hemenway, 1978, p. 697). In other words, given how the stimuli were created, rotational symmetry had also near reflectional symmetry, especially because of the presence of few salient parts on each side of a main axis, and when the orientation of the axis of reflection was unpredictable this lead to long RT for rotational symmetry. In general, this importance of parts is consistent with our argument about polarity, as it is the alternation of convexity and concavity that creates the parts of a shape.

10.3. Experiment 3b: Detection of rotation—results and discussion

Mean RT and errors are shown in Fig. 4 (right column).

10.3.1. Target detection

In the reaction time data for targets, there was a highly significant effect of shape ($F(3,23) = 15.17$, $p < 0.001$), with people being significantly slower on the one-object shape than on the other shapes. Moreover, there was an effect of orientation ($F(1,23) = 15.17$, $p < 0.001$) with people being faster when the stimulus was below the centre of rotation. The same pattern was evident in the error data (shape: $F(3,23) = 10.76$, $p < 0.001$; orientation: $F(3,23) = 6.41$, $p = 0.019$). Errors were on average higher than in Experiment 3a (a range of 0%–30%, compared to 0%–8%). People were much slower and less accurate at detecting rotation for the one-object shape, suggesting a one-object disadvantage for detecting rotation: the inverse of the one-object advantage for reflection previously demonstrated, but consistent with Experiments 1 and 2.

10.3.2. Foil rejection

The repeated measures ANOVA confirmed significant effects of shape ($F(3,23) = 8.99$, $p < 0.001$) and foil type ($F(1,23) = 110.10$, $p < 0.001$) on foil rejection. Moreover, there was an interaction between shape and foil type ($F(3,23) = 3.55$, $p = 0.018$). People were faster to reject the baseline and one-object shapes, and they were faster to reject the foils that had reflection than the random foils, which suggests a strategy of rejection of reflection followed by discrimination between random foils and rotation.

The analysis of errors confirmed an effect of shape ($F(3,23) = 7.76$, $p < 0.001$) foil type ($F(1,23) = 54.94$, $p < 0.001$) and an interaction between the two ($F(3,23) = 6.50$, $p < 0.001$). The errors for the rejection of reflected foils were exceptionally low—all below 5%—and consequently there was a floor effect (a ceiling effect in performance) and no differences were found for the different shapes in the reflected foil condition. However, the error rate for rejecting the random foils was higher (more comparable to that for the targets), suggesting that people had problems discriminating between the two in a timed task.

In summary, Experiment 3b suggests that different types of transformations are different for the visual system, and opposite effects of closure (a one-object advantage or a one-object disadvantage) can be detected even within the same set of trials by analysing target detection and foil rejection separately. We take this as further evidence that these two effects are not the result of different strategies, such as performing a mental rotation for two-objects stimuli ("lock-and-key"). Instead, we speculated that this effect may be due to the fact that closure makes the mismatch in polarity even more salient in the rotated stimuli, and such mismatch makes the object appear highly irregular.

Considering Experiments 3a and 3b together, we can see that in the first experiment where the task can be performed by responding only to reflection (or absence of reflection), observers are fast and closure always has a facilitatory effect. This is consistent with reflection being an easier target to detect. The observers need not concern themselves with any processing beyond detection of reflection and when reflection is not present they can respond with the key that indicates target absent. Note that, unlike what was found in Experiments 1 and 2, the closure advantage for detection of reflection was present for both target and foil data. Moreover, responses to the baseline stimuli were faster than to the two-objects and pacman stimuli. In this sense we suggest that the findings of Experiment 3a are consistent with a two-objects cost.

In Experiment 3b instead, reflection may be perceived quickly and in this case observers respond quickly (again with a facilitatory effect of closure) but in the absence of reflection they need to discriminate between random and rotation, and this is the slower process that is actually hindered by closure (but only for targets). Moreover, in the case of rotated stimuli even the baseline stimuli are responded to faster than to the one-object stimuli. In this sense we suggest that this effect found in Experiment 3b is due to a one-object cost. We suggest that this problem in responding to the one-object rotated contours is due to the mismatch in contour polarity.

11. General discussion

Using a reaction time paradigm we have explored the effect of closure on detection of contour rotation. The goal was to test whether rotation would be affected by closure in a way similar to reflection or similar to translation, in the former case the closure of the contours should facilitate detection of regularity, in the latter it should hinder detection (Bertamini et al., 1997). The results clearly show that in the case of detection of rotation, just like in detection of translation, the closure of the contours is detrimental. This goes against the predictions based on (a) a one-object advantage due to attentional or computational costs; (b) an advantage for smaller objects due to the size of the area to be attended to. It also goes against the prediction that rigid transformations are treated by the visual system in the same way that they are treated in geometry, namely that all types of rigid transformations in the plane are a family and are closely related (this point has been clearly recognised before in the literature, e.g. Mach (1886), Van der Helm & Leeuwenberg (1996), Wagemans (1997, 1999b)). We are not arguing that a one-object advantage does not exist, but rather that a different and powerful factor must be countering the one-object advantage in our experiments.

A number of positive conclusions can also be drawn from our results. (a) First of all, what was described as a between-object advantage in the case of detection of translation ("lock-and-key" process, Bertamini et al., 1997) is better described as a "gap" advantage, or even more precisely as a cost of closure. Experiments 1 and 2 show that, no matter how many objects are present in the display, it is faster to detect a translation or a rotation when the contours are defining an aperture, instead of closing a surface (an inspection of the stimuli in Figs. 1 and 3 would confirm this statement). (b) In Experiment 2 we interviewed participants to see whether the effect of closure was related in any way to a particular conscious strategy. We found that some people claimed to have used a strategy of matching parts as in a jigsaw puzzle, however this group did not perform differently from the rest. (c) The importance of closure is consistent with the central role that contour polarity plays in processing shape (e.g., Baylis & Driver, 2001; Bertamini, 2001; Hoffman, 1998; Hulleman et al., 1998). Polarity information in itself cannot explain the aperture advantage, but we speculate that (although prima facie this may seem paradoxical) it is an advantage in processing polarity in closed objects that leads to the perception of objects with rotated and translated contours as less regular even than similar contours that are not part of a closed object. Consistent with such a hypothesis, we found in Experiment 3a that objects with rotated contours are easier to reject (when detecting reflection) than even random objects. Experiment 3b also confirmed that when detecting rotation there is a cost of closure for target detection (as in Experiment 1 and 2) while at the same time there is closure advantage for rejection of reflected foils.

We believe that our hypothesis on the role of polarity, namely that polarity information hinders detection of translation and rotation in closed objects, is also supported by another known fact. The difference between reflection on the one hand, and translation and rotation on the other, is quite large in terms of RT and also phenomenologically salient. However, it is not true that translations and rotations are always hard to perceive. They are quite salient when closure is completely absent, such as in rotational and translational Glass patterns (with small displacements) (Glass, 1969; see Van der Helm & Leeuwenberg, 1996; Wagemans, 1999b; see also Royer, 1981, for a different type of stimuli).

In conclusion, our results are consistent with Wagemans et al.'s (1993) contention that it is necessary to study the detection of symmetry (and regularity in general) within the context (and theory) of shape perception. The main finding is that there is no within-object advantage for detection of rotation, and that instead rotation is easier to perceive when the contours define an aperture or a gap. The hypothesis that this is linked to the salience of polarity information in closed objects, although supported by the results of Experiment 3, requires further investigation.

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