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Detection of symmetry and perceptual organization: The way a lock-and-key process works

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Abstract

We studied the speed with which observers could detect symmetry in drawings that incorporated symmetric contours – related by reflection or translation – within single objects or across different objects. We asked observers to perform a speeded decision whether pairs of contours are the same, i.e., related by reflection or by translation, or different. When the contours belong to a single object, observers are faster to see the relation between contours when they are related by reflection than by translation. When the contours belong to different objects, observers are faster to see the relation between the contours when they are related by translation than by reflection. We tested whether this advantage of translation is due to a lock-and-key process. We first tested our hypothesis by manipulating the correspondence of the features, so as to make matching more difficult. This change did not produce the predicted pattern of results. We performed a second manipulation to change the appearance of the objects: we increased the *prägnanz* of the objects by changing the type of lines used to connect the contours. Results indicate that perceptual organization can alter the detectability of symmetry.

PsycINFO classification: 2323; 2346

Keywords: Visual perception; Visual discrimination; Reaction time; Mirror image; Prägnanz

1. Introduction

Symmetric patterns are created by isometric transformations. An isometric transformation, or isometry, is a rigid transformation that maps a figure onto itself. Reflection (b d) and Translation (b b) are isometries. When we see that two contours are translated

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or reflected we must have discovered how features in each of the contours correspond to each other. In other words, we must discover how the isometric transformation maps one figure onto another.

Most models of symmetry perception deal only with reflection. Several researchers have proposed that reflection is detected by a two-stage process (Jenkins, 1983a,b; Palmer and Hemenway, 1978). In the first stage the orientation of an axis of reflection is identified; in the second stage the elements or features perpendicular to this axis are compared. In particular, Jenkins studied dot patterns and concluded that in the first stage the common orientation of virtual lines between pairs of dots is extracted, then in the second stage pseudo-features of the configuration are compared. In a model that is similar to Jenkins' but with a different mechanism, Wagemans et al. (1993) proposed that a bootstrapping process is involved in the detection of symmetry. The process is based on the virtual quadrangles that can be formed by connecting four features (e.g., dots) of the pattern. Wagemans et al.'s theory can explain why reflection is easier to detect than translation (Mach, 1886/1995); it is because (1) the quadrangles for reflection (i.e., symmetric trapezoids) share an axis of orientation, whereas quadrangles for translation (i.e., parallelograms) do not; (2) therefore the orientation axes of reflection needs to be computed only once per object, whereas the orientation axes of translation must be computed anew for each quadrangle.

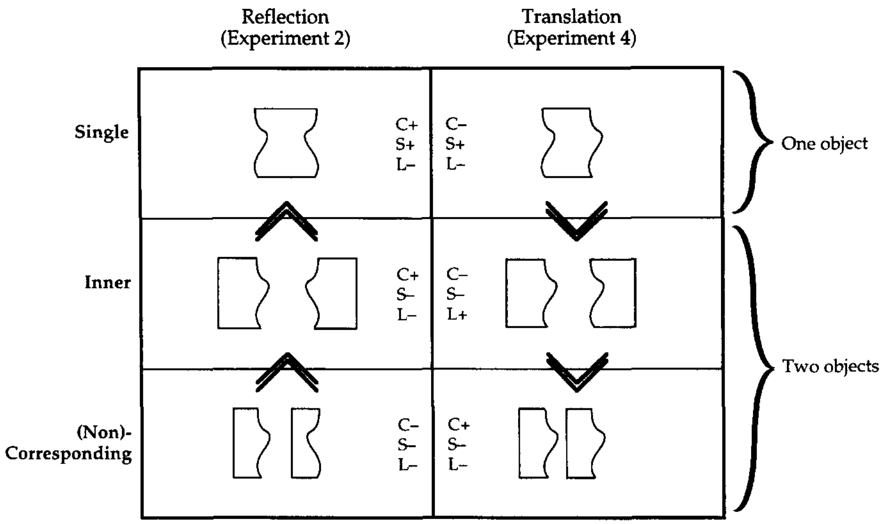
Symmetry is often cited as an important factor in object segregation and representation. After edges are extracted, reflectional symmetry and other principles of good Gestalt create the basic components of the object representation (Biederman, 1987; Marr and Nishihara, 1978).

There is a problem here: if we cannot perceive symmetry without first identifying a region and its main orientation, it must be secondary to more basic object segregation processes. On the other hand, reflectional symmetry has always been thought to be fundamental in defining an object. The paradox is only present if we believe that the visual system consists of independent stages each of which performs a specific process and then passes its output to the next stage. This kind of model, although common, is inappropriate for biologically plausible neural networks. Instead, even processes that belong to different stages can constrain each other's output. This makes research more difficult, and implies that it is important to study the interaction between different processes. In this study we are doing just that: looking at the interaction of symmetry detection with other grouping principles.

Kanizsa (1979) has demonstrated how symmetry affects figure-ground organization. The goal of our study is to find how figure-ground organization affects the detection of symmetry. Because symmetry is detected fast and effortlessly, it is not obvious to what extent other grouping principles may affect the subject's performance in a detection task. The interplay between different grouping principles (e.g., closure) that define an object, could facilitate the detection of symmetry.

2. Differences between reflection and translation

There is an important difference between perception of reflection and perception of translation. Translation and reflection are similar in the geometrical sense – they are



C+ contour pairs have equal convexity and concavity interpretation
S+ contour pairs belong to the same object
L+ contour pairs can be matched in a lock-and-key fashion

C– contour pairs have opposite convexity and concavity interpretation
S– contour pairs belong to different objects
L– contour pairs cannot be matched in a lock-and-key fashion

Fig. 1. RT results from Experiments 2 and 4 in Baylis and Driver (1995). The symbol $\overset{\vee}{\vee}$ means significantly longer RT for the condition above, and $\overset{\wedge}{\wedge}$ means significantly longer RT for the condition below. The symbols C, S, and L refer to the three hypothesized processes as explained in the legend.

both isometries – but they differ in what they signal about objects. Reflection (disregarding natural mirrors, such as bodies of water) is most likely to be present within a single object where the symmetry is the product of growth processes: for example in the human body, a nest, or a tree. Translation on the other hand signals the multiple occurrence of similar objects. Therefore reflection may be more useful than translation in defining and segregating objects from their background (Rock, 1983).

This observation may be a key to understanding the differences in performance observed for the perception of translation and reflection. Not only is reflection detected faster, but Baylis and Driver (1994) have shown that the detection of translation requires a serial comparison of features, whereas the detection of reflection does not.

Baylis and Driver (1995) have conducted experiments with contours that had reflectional and translational symmetry. Their stimuli, of which we were not aware at the time we devised our experiments, are similar to ours. In Fig. 1 we present a summary of their findings. The illustrations are not faithful to the original appearance of the stimuli but show the information carried by them better than words could do. The labels on the left side are those used by Baylis and Driver, the ones on the right are ours. Baylis and Driver's interpretation of these results is the following:

1. RTs are longer for comparisons between objects than comparisons within objects

because of an attentional cost of performing a comparison between objects (as Baylis and Driver, 1993, found earlier).
2. RTs are longer when the assignment of convexity and concavity for one of the contours is different from the assignment for the second contour. The assignment may depend on the minima rule proposed by Hoffman and Richards (1984).
3. As an exception to 1, the within-object advantage is not present for translation. Comparisons between objects are faster if the contours are translated instead of reflected. Baylis and Driver (1995) suggest that the pieces fit together like jigsaw pieces, and maybe a jigsaw-matching strategy is adopted. This is the same explanation that we have proposed and called lock-and-key matching (Bertamini et al., 1993).

Thus three effects (number of objects, convexity, and lock-and-key) are necessary to account for the findings summarized in Fig. 1. Any two of them will not do.

3. The way lock-and-key works

Explaining the fact that detection of translation is faster between two objects than within one object by calling attention to the way the two pieces fit as a lock and a key does no more than provide a name for the phenomenon. This paper is the first study to investigate how a lock-and-key process might operate to allow the detection of translation. We believe it is necessary to study this problem in the broader context of detection of symmetry.

Our Experiment 1 replicates and generalizes a basic result: the interaction between type of symmetry and organization of the contours into objects. We manipulated figure-ground by connecting the contours in different ways, therefore embedding them in one object or in two different objects, without introducing edges of different luminance polarity. In Experiment 1 we also inquired whether subjects use different strategies for one or the other kind of symmetry by comparing performance when they are interspersed in the same block of trials and when they are separated by block.

Experiment 2 tested a hypothesis on the nature of the lock-and-key process, and failed to support the basic prediction that a match is performed by translating the parts on the plane.

Finally Experiments 3 and 4 introduced a new manipulation that alters the prägnanz of the two parts of the image. By that we mean the perception of parts as independent *good* figures or as pieces of a more global figure. This manipulation has a larger effect on symmetry detection.

4. Experiment 1

Our main goal in conducting the first study was to demonstrate the interaction of detection of symmetry (translation and reflection) with grouping. Reflection should be more easily detected within objects, and translation between objects.

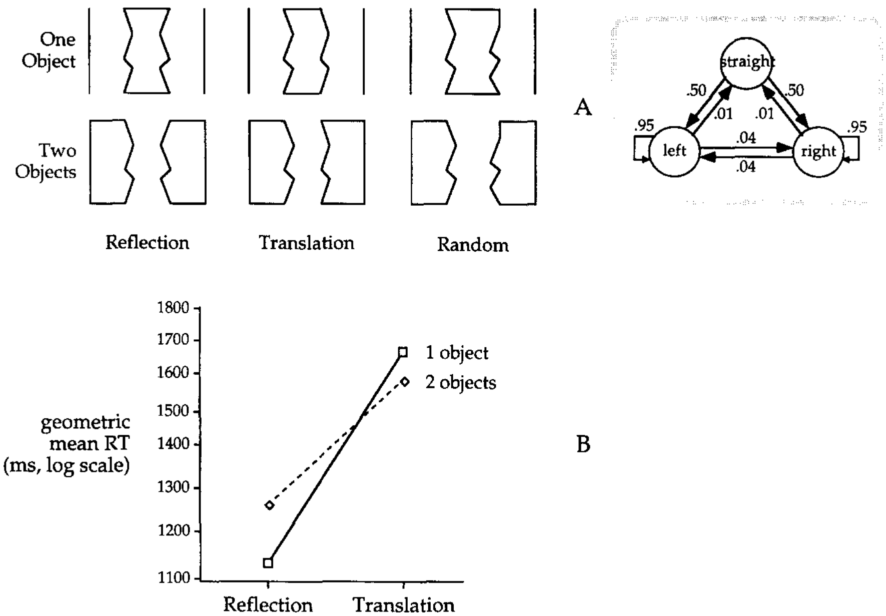


Fig. 2. (A) Line drawings used in Experiment 1. The lines to be compared were generated with a modified random walk for each trial. The probability of changing direction are given in the inset. (B) Geometric means of reaction time in ms for Experiment 1. Lines are used in order to help in the visualization of mean changes and interactions.

We used two types of symmetry: translation and reflection. In the one-object condition, two contours were connected to form a single object. In the two-object condition, two contours were connected so that they became parts of different objects (see Fig. 2A). We added two additional vertical lines to the one-object condition to keep the overall size of the display comparable to the two-object condition. From the point of view of perceptual organization, it is the principle of closure that determines the number of objects. Palmer and Rock (1994) have claimed that a more basic principle, called common region or uniform connectedness, is at work in this kind of configuration. This distinction however does not alter the interpretation of our results.

For one group of subjects we presented each symmetry type separately in two blocks of trials. For a second group of subjects we intermixed the symmetry types. We asked the subjects to detect the presence of a symmetry, regardless of type. We introduced this independent variable to discover whether different strategies were adopted by subjects when they were looking for a particular kind of symmetry, as opposed to any kind of symmetry.

We introduced another new feature to this experiment: the stimuli are line drawings; therefore the contours are not edges of regions of different luminance. We know from Baylis and Driver's (1995) experiments that such changes in polarity are important. In our experiment closure of the line contours is the only information that distinguishes the one-object condition from the two-object condition, and it is a feature of the overall configuration; in contrast, the change in polarity is present locally. Our choice of line drawings also minimized luminance changes between trials, making the one-object and the two-object conditions as similar as possible.

To create the contours, we used a line that changed direction according to a random walk algorithm. The contour looked like a line with a small number of sharp turns. We preferred sharp angles over smooth curves because they avoid difficulties in matching the contours due to the ambiguity of their three-dimensional interpretations. Rock et al. (1989) have shown that comparison of shapes by mental rotation is more accurate when the shapes contain angles than when the shapes are smooth.

4.1. Method

4.1.1. Subjects

Sixteen subjects participated (eight males and eight females). They were undergraduate students at the University of Virginia and were fulfilling a requirement for an introductory psychology course. All subjects had normal or corrected-to-normal vision. They were naive with respect to the hypotheses.

4.1.2. Apparatus and stimuli

A Macintosh SE computed and displayed the stimuli. The stimuli appeared as a black outline on a white background. We created three pairings of contours: translation, reflection and random (Panel A of Fig. 2). Each stimulus consisted of two probabilistically generated contours. In the one-object condition we connected these contours to each other by two horizontal lines to form a single shape. In the two-object condition we did not connect these contours, but formed two shapes by the addition of two horizontal and one vertical line to each.

Each probabilistic contour was drawn by moving a line down 2 pixels, then either not moving or moving left or right 1 pixel. This line was constrained to move within a region 20 pixels wide. If the computed direction of the line caused it to cross a barrier, the direction was changed. Because the end point could be different for every contour generated, the starting point was randomly determined within a range of ± 10 pixels from the midpoint of the two boundaries. The display subtended about 12° vertically, and 4.8° horizontally. The Markov chain describing the generating algorithm is shown in the inset of Fig. 2A.

4.1.3. Design and procedure

Eight subjects (four males and four females) were run in the mixed group, and eight subjects in the blocked group; we call this between-subjects factor MIX. They participated in two blocks for a total of 360 trials. In each block we presented 90 symmetry trials and 90 random trials. In the blocked group TYPE OF SYMMETRY was blocked (four subjects had translation in the first block and reflection in the second, whereas this order was reversed for the remaining four subjects). Therefore, for this group, the task was different for the two blocks; subjects were aware that the signal was reflected contours in one block and translated contours in the other. For the mixed group the trials on the two blocks were identical. We instructed subjects to consider both kinds of symmetries as signal, and the random condition as noise.

We told subjects to press the 'k' key on the computer keyboard for signal, and the 'd' key for noise. Before the stimulus appeared we presented a fixation mark centered on the monitor. The stimulus lasted until the observer responded; a new trial started after a blank screen of 200 ms. The instructions stressed response speed as well as accuracy.

4.2. Results

We brought the RT distributions close to normality with a logarithmic transformation (for a reason to expect lognormal RT distributions see Ulrich and Miller, 1993). We censored RTs greater than 5 s (less than 2% of the data). We did not analyze the 'different' trials. The overall error rate was 3.7%.

4.2.1. We found the expected interaction between the type of symmetry and number of objects

Panel B in Fig. 2 shows the geometric means of the RT. The figure depicts a crossover interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS: for reflection, subjects responded to one-object stimuli 129 ms faster than to two-object stimuli; whereas for translation, they responded to one-object stimuli 81 ms slower than to two-object stimuli. We saw no evidence of a speed–accuracy trade-off for any of the subjects.

We performed an ANOVA with two within-subjects factors: TYPE OF SYMMETRY (reflection and translation), and NUMBER OF OBJECTS (one and two), and one between-subjects factor: MIX (mixed and blocked symmetry). This analysis confirmed the crossover interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS ($F(1,14) = 26.11$, $p = 0.00016$).

We also performed planned Wilcoxon matched-pair signed-rank comparisons to confirm this interaction. For reflection, subjects responded faster to one-object stimuli than to two-object stimuli ($N = 16$, $T = 16$, $p = 0.003$). But for translation they responded more slowly to one-object stimuli than to two-object stimuli ($N = 16$, $T = 0$, $p = 0.0002$).

We also examined individual data. Fourteen of the 16 subjects show the crossover interaction TYPE OF SYMMETRY by NUMBER OF OBJECTS (by Sign Test, we reject H_0 that half the subjects show the interaction, $p = 0.0021$).

4.2.2. We did not find that conditions favoring different strategies affected the interaction just discussed

We first note a large effect of TYPE OF SYMMETRY ($F(1,14) = 138.40$, $p = 1.2 \times 10^{-8}$): subjects detect reflection 432 ms faster than translation. We also found an interaction between MIX and TYPE OF SYMMETRY: the advantage of reflection over translation was 501 ms in the blocked group, whereas it was 344 ms in the mixed group ($F(1,14) = 11.14$, $p = 0.005$). However, we could not confirm a three-way interaction between MIX, TYPE OF SYMMETRY, and NUMBER OF OBJECTS ($F(1,14) = 1.113$).

We now turn to a less important result. We confirmed a small effect of NUMBER OF OBJECTS ($F(1,14) = 6.81$, $p = 0.02$): subjects detected symmetry of contours that belong to a single object 295 ms faster than contours that belong to different objects.

4.3. Discussion

As expected, detection of reflection is faster than detection of translation. The interaction between MIX and TYPE OF SYMMETRY shows that although reflection is always faster, this difference is smaller in the mixed condition. This is the only effect of mixing the two types of symmetry.

We observed a crossover interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS: whereas one object makes the task faster for reflection, the opposite is true for translation. We observed this interaction whether the two types of symmetries were in the same or in different blocks of trials. Moreover the presence of local polarity change (absent in our line drawings) is not critical for the interaction. Notice that an optimal strategy would be to ignore the lines that surround the contours to be compared, but the results show that this was not a strategy available to our subjects.

According to Baylis and Driver (1993) the comparison of features belonging to one object is faster than the comparison of features belonging to two objects because of the additional cost of dealing with two object representations. But why is detection of translational symmetry faster in the case of two objects? In the introduction we suggested that this advantage is due to a lock-and-key match between the two objects when the contours are translated. This hypothesis is tested in the following experiments.

5. Experiment 2a

Experiment 1 has established a two-way interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS. We wish to focus on the fact that for translation two-object stimuli are judged faster than one-object stimuli. This may be the result of a mental transformation that matches the objects the way a key matches a lock. Therefore it would have been convenient to drop the reflection condition from our next experiments and make them simpler. However, we decided against this idea for two reasons. First, we wish to manipulate the appearance of the display in a way that is new and may have unpredictable effects on the basic interaction. Secondly, we need the reflection condition as a control to show that perception of reflection, unlike translation, is always faster for one-object stimuli because no lock-and-key matching is possible.

Experiment 2a tests the possibility that people perform a virtual translation in the plane of the two objects to match them. We changed the display to undermine this strategy while keeping translation perfect. This was achieved by creating two conditions that we call *jigsaw* matching and *lock-and-key* matching. These two kinds of display are shown in panel A of Fig. 3. In the first case the two objects cannot be virtually translated and matched within the plane without collision, in the second case they can be translated without collision. The reason for this manipulation is to study the origin of the lock-and-key advantage, one way of thinking about it is to consider the lock-and-key matching as a form of internalized transformation. There is no logical need to perform a translation to compare the contours of the two objects, just as there is no logical need to perform a mental rotation to compare letters, but the visual system may be constrained by what appears to be an internalization of the nature of the physical transformation (Shepard, 1994).

5.1. Method

5.1.1. Subjects

Twenty subjects participated. They were undergraduate students at the University of Virginia and were fulfilling a requirement for an introductory psychology course. All subjects had normal or corrected-to-normal vision. They were naive with respect to the hypotheses.

5.1.2. Apparatus and stimuli

Stimuli were computed and displayed on a Macintosh IIci. Each stimulus appeared as a black outline on a white background. The display subtended approximately 11.2° horizontally and 5.2° vertically. The procedure was similar to Experiment 1, but a new variable was introduced: TYPE OF MATCHING (consisting of two conditions: jigsaw matching and lock-and-key matching). The stimuli were line drawings, having protruding or receding features, as shown in Fig. 3A. Each contour had two features with a variable vertical position and a variable size, the protrusion (or recession) was between 10 and 22 pixels. On every trial we presented a new pair of contours created with a new randomization process. We used this method to equate the area of the figures in the jigsaw and lock-and-key conditions, because we used the same features, only joined to the rest of the object in different ways.

The condition where contours were different (noise trials) is not shown in Fig. 3A. We created it by using the same algorithm to produce two different contours instead of translating or reflecting the first contour. Therefore the noise trials were identical to the symmetry trials but for the relationship between the two contours.

5.1.3. Design and procedure

The variables were all within-subjects: TYPE OF SYMMETRY (reflection vs. translation), NUMBER OF OBJECTS (one vs. two), and TYPE OF MATCHING (jigsaw vs. lock-and-key). Therefore we had eight unique stimulus conditions. Every subject saw 6 blocks of 96 trials (12 repetitions of each distinct stimulus condition), with pauses at the end of each block. At these times we had the computer display the subject's average RT and number of incorrect responses.

Reflection and translation trials, as well as jigsaw and lock-and-key trials were randomly mixed. Subjects were instructed to press '/' on the keyboard if they perceived the two contours as different, and 'z' if they perceived the two contours as symmetric.

5.2. Results

We used the same data censoring and transformation as we did in Experiment 1. The overall error rate was 7.7%. In general, responses were faster than in Experiment 1, possibly because the contours were taller, and more rich in details.

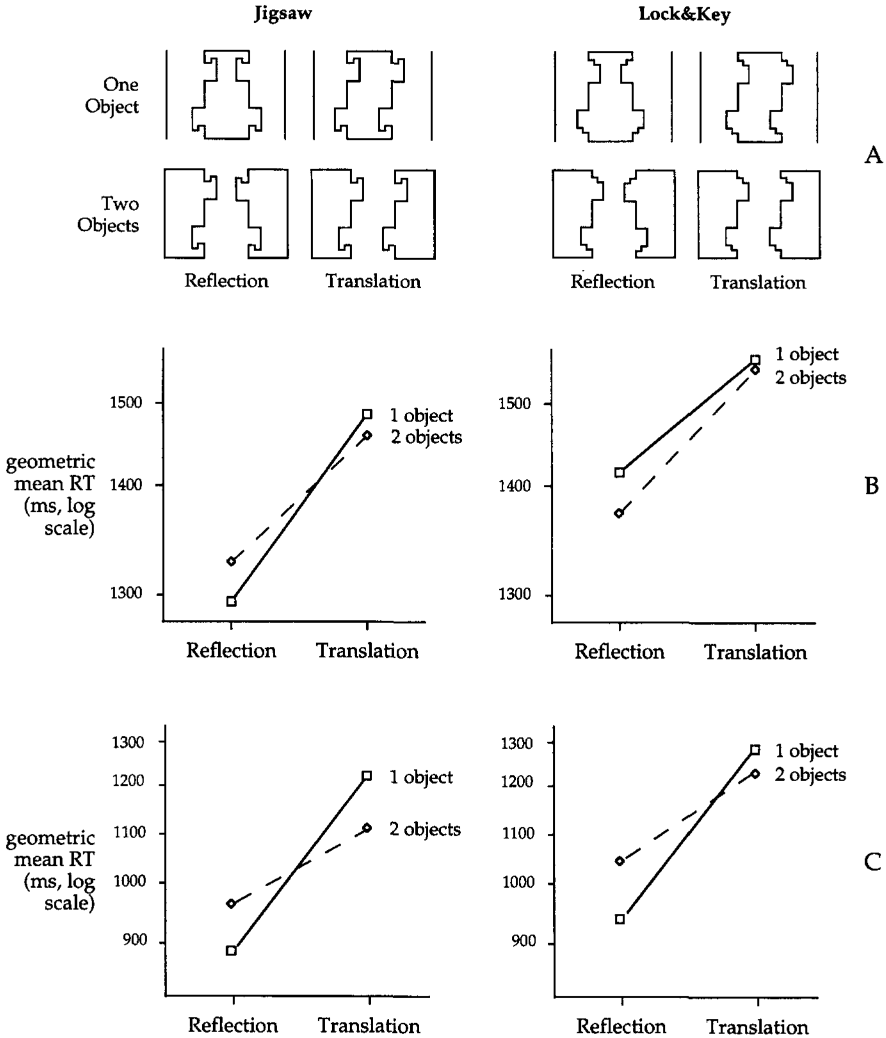


Fig. 3. (A) Line drawings used in Experiment 2a. The random condition is not shown; it had displays identical to those in the two experimental conditions but for the fact that no relationship between the left and right contours was present. (B) Geometric means of reaction time in ms for Experiment 2a. (C) Geometric means of reaction time in ms for Experiment 2b.

5.2.1. We found a three-way interaction between type of symmetry, number of objects, and type of matching

Fig. 3B shows the three-way interaction between TYPE OF SYMMETRY, NUMBER OF OBJECTS, and TYPE OF MATCHING. A repeated measures ANOVA with TYPE OF SYMMETRY, NUMBER OF OBJECTS, and TYPE OF MATCHING as independent variables confirmed the three-way interaction ($F(1,19) = 5.40$, $p = 0.03$). The direction of this interaction is opposite to our predictions, because we expected the jigsaw condition to eliminate the crossover interaction.

Planned Wilcoxon matched-pair signed-rank comparisons were performed on the conditions of Fig. 3B. None of the four pairwise comparisons was significant ($N = 20$, $85 < 99$, $0.23 < p < 0.41$).

5.2.2. *We replicated an advantage for reflection over translation*

The ANOVA showed a main effect of TYPE OF SYMMETRY ($F(1,19) = 16.68$, $p = 0.0006$). Consistent with the first experiment, detection of reflection was 149 ms faster than detection of translation.

The analysis also showed an effect of TYPE OF MATCHING ($F(1,19) = 10.48$, $p = 0.004$), responses for the jigsaw stimuli were significantly faster than for the lock-and-key stimuli.

5.3. *Discussion*

The lock-and-key hypothesis is not confirmed by this experiment. We predicted that in the lock-and-key condition the two-object condition would be faster than the one-object condition for translation, as in Experiment 1. In the jigsaw condition however we expected this advantage to disappear. To our surprise, Fig. 3B shows the opposite pattern. The crossover interaction is still present for jigsaw, but changed to a non-crossover interaction for lock-and-key stimuli, as confirmed by a three-way interaction.

Although this is not conclusive evidence against the hypothesis of a perceptual lock-and-key matching, we need to explain what happened in the lock-and-key condition. We will revisit this issue in the general discussion.

6. Experiment 2b

In Experiment 2a we replicated the basic interaction of NUMBER OF OBJECTS with TYPE OF SYMMETRY, but the effect of TYPE OF MATCHING was in the direction opposite to the one we predicted. A result contrary to expectations is always intriguing, so we replicated the experiment with some changes. We separated the TYPE OF MATCHING (jigsaw and lock-and-key) in different blocks of trials so as to maximize our power to detect differences between these two conditions. We also used filled objects, which are closer to those used by Baylis and Driver (1995) than the ones we used in Experiment 2a. Moreover, to avoid the possibility that people could pay attention only to the central region of the screen and therefore not process the whole configuration, the stimulus appeared at a random position on the screen.

6.1. *Method*

Anything we do not specify here is identical to the method for Experiment 2a. Thirteen subjects participated. Every subject saw 4 blocks of 264 trials. The Jigsaw condition and Lock-and-key condition were in blocks JLJL for half the subjects and in blocks LJLJ for the other half.

6.2. Results

We used the same data censoring and transformation as we did in Experiment 1. The overall error rate was 13.9%.

6.2.1. Three-way interaction between type of symmetry, number of objects, and type of matching

Results for the three-way interaction of the geometric means are plotted in Fig. 3C. However, a repeated measures ANOVA did not show a significant three-way interaction ($F(1,12) = 0.424$). On the other hand, the ANOVA confirmed an interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS ($F(1,12) = 47.49$, $p = 0.000017$), consistent with the results of Experiment 1: For reflection, subjects responded to one-object stimuli faster than to two-object stimuli; whereas for translation, they responded to one-object stimuli slower than to two-object stimuli.

We performed planned Wilcoxon matched-pair signed-rank comparisons on the conditions of Fig. 3C. For jigsaw stimuli in the reflection condition, one-object stimuli were responded to faster than two-object stimuli ($N = 13$, $T = 5$, $p = 0.0023$); vice versa for translation, two-object stimuli were responded to faster than one-object stimuli ($N = 13$, $T = 7$, $p = 0.0035$). For lock-and-key stimuli in the reflection condition, one-object stimuli were responded to faster than two-object stimuli ($N = 13$, $T = 0$, $p = 0.0007$); for translation however, two-object stimuli and one-object stimuli differed marginally ($N = 13$, $T = 22$, $p = 0.05$).

6.2.2. We replicated an advantage for reflection over translation

The ANOVA also confirmed a main effect of TYPE OF SYMMETRY ($F(1,12) = 53.74$, $p = 9.09 \times 10^{-6}$), observers responded 413 ms faster to reflection stimuli than to translation stimuli. Finally, we found an interaction of TYPE OF MATCHING and NUMBER OF OBJECTS ($F(1,12) = 7.17$, $p = 0.02$).

6.2.3. Analysis of the errors

Because of the higher error rate, above 10%, we tested the logit of the percentage of correct responses in a second ANOVA with the same design as the ANOVA on the response time. We found a main effect of TYPE OF SYMMETRY in which more errors were committed for translation than for reflection ($F(1,12) = 13.67$, $p = 0.003$), as well as a main effect of NUMBER OF OBJECTS ($F(1,12) = 34.62$, $p = 0.00007$), more errors were committed for one-objects. We confirmed an interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS ($F(1,12) = 10.29$, $p = 0.0075$). No other effects were confirmed. The direction of the differences was the same as that of the response time, and a plot of the means shows the same pattern of Fig. 3C.

6.3. Discussion

In this experiment we obtained essentially the same effects as in Experiment 2a. Overall the RT are shorter than in Experiment 2a and the error rate higher. However, Panels B and C of Fig. 3 exhibit the same pattern, the three-way interaction is now not significant, but the means show here as in Experiment 2a that the effect of Jigsaw goes in the opposite direction with respect to our hypothesis. This is confirmed by the Wilcoxon tests.

7. Experiment 3

In this experiment we manipulated the configuration in a new way. Our main goal was still to look at the relationship between the perceptual organization of a display and the detection of symmetry. In Experiment 1 we saw that reflection and translation behave differently because they are pulled in opposite directions by a simple figural organization of the lines surrounding the contours. In particular we suggested that in the two-object condition translation is facilitated by a lock-and-key matching of the two pieces. If this is true, then we expect that any variable that makes two pieces appear as coming from the same original object will lead to this result. Vice versa, any variable that makes two pieces appear as independent objects will hinder the task of comparing the contours. [1]

Once matched two parts can create a regular figure or an irregular figure when the contours on the outside are irregular. Panel A in Fig. 4 depicts the stimuli used in Experiment 3 and the new conditions we call *high-prägnanz* and *low-prägnanz*. Note that for the high-prägnanz stimuli, the lock-and-key match forms a complete and simple object, i.e., a rectangle. For the low-prägnanz stimuli the lock-and-key match is still possible but a rectangle is not formed. We expected the effect size to be small, therefore we ran 30 subjects in this experiment to increase power.

One possible objection to our new stimuli is that outside contours of the low-prägnanz figures might interfere with the task. This may be true but it cannot explain the expected result. First, the outside contours have no relationship with the inside contours. More importantly, we predict a three-way interaction and an interference process could not explain why PRÄGNANZ affects the interaction of NUMBER OF OBJECTS with TYPE OF SYMMETRY.

7.1. Method

7.1.1. Subjects

Thirty subjects participated. They were undergraduate students and were fulfilling a requirement of an introductory psychology course. All subjects had normal or corrected-to-normal vision. They were naive with respect to the hypotheses.

7.1.2. Apparatus and stimuli

The apparatus was identical to Experiment 2. Stimuli were line drawings on a white background and are illustrated in Fig. 4A. On each trial, contours were generated with a

[1] When results of this study were presented by MB at a meeting in Trieste (November, 1993), Paolo Bozzi suggested this manipulation of the phenomenal appearance of the parts.

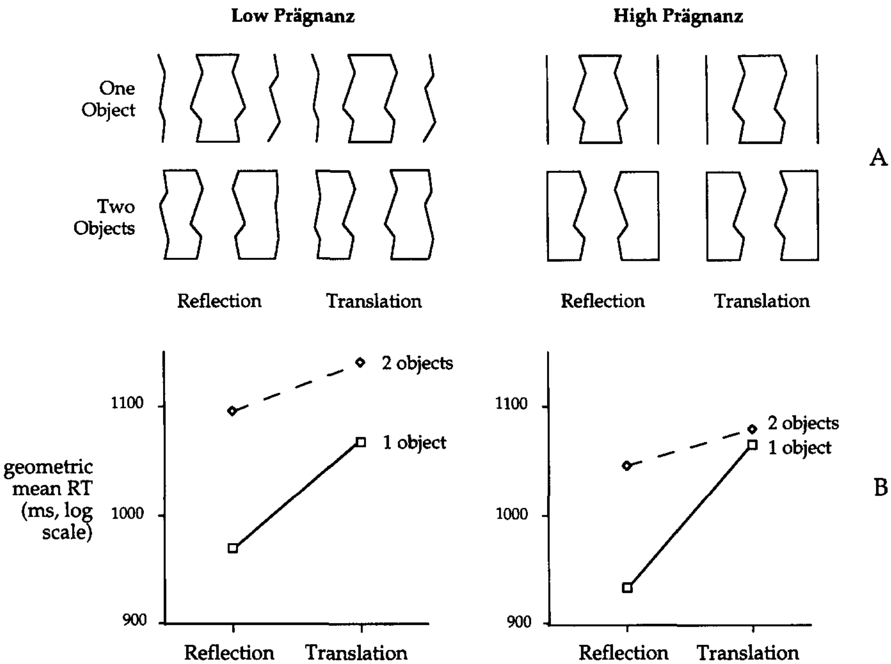


Fig. 4. (A) Line drawings used in Experiment 3. (B) Geometric means of reaction time in ms.

line that had four turns. Position of the turns and direction of the line was randomly chosen for each new trial.

7.1.3. Design and procedure

The procedure was identical to that of Experiment 2. We created three within-subjects variables in a factorial design: TYPE OF SYMMETRY (reflection and translation), NUMBER OF OBJECTS (one and two), and PRÄGNANZ (high and low), for a total of eight stimulus conditions. Every subject saw 4 blocks of 264 trials (with two rest breaks per block). High and low prägnanz were separated in blocks HLHL for half of the subjects and in blocks LHLH for the other half.

7.2. Results

We used the same data censoring and transformation as we did in Experiment 1. The overall error rate was 4.6%.

7.2.1. Three-way interaction between type of symmetry, number of objects, and prägnanz

Results for the three-way interaction of the geometric means are plotted in Fig. 4B. The figure shows that the interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS was different in the high and in the low conditions and this difference was in the expected direction. However, a repeated measures ANOVA with TYPE OF SYMMETRY, NUMBER OF OBJECTS, and PRÄGNANZ as independent variables did not confirm a three-way interaction ($F(1,29) = 1.535$).

Planned Wilcoxon matched-pair signed-rank comparisons were performed on the conditions of Fig. 4B. For low prägnanz stimuli in the reflection condition, one-object stimuli were responded to faster than two-object stimuli ($N = 30$, $T = 3$, $p = 1.77 \times 10^{-6}$); the same was true for translation, one-object stimuli were responded to faster than two-object stimuli ($N = 30$, $T = 43$, $p = 0.000049$). For high prägnanz stimuli: for reflection, one-object stimuli were responded to faster than two-object stimuli ($N = 30$, $T = 9$, $p = 2.14 \times 10^{-6}$); for translation, two-object stimuli and one-object stimuli did not differ ($N = 30$, $T = 215$, $p = 0.36$).

7.2.2. Other effects

The repeated measures ANOVA showed main effects of TYPE OF SYMMETRY ($F(1,29) = 26.61$, $p = 0.000016$), NUMBER OF OBJECTS ($F(1,29) = 43.52$, $p = 3.14 \times 10^{-7}$) and PRÄGNANZ ($F(1,29) = 32.49$, $p = 3.64 \times 10^{-6}$). As expected, subjects responded to reflection stimuli 86 ms faster than to translation stimuli, to one-object stimuli 86 ms faster than to two-object stimuli, and to high prägnanz stimuli 40 ms faster than to low prägnanz stimuli. A significant interaction was present between PRÄGNANZ and NUMBER OF OBJECTS ($F(1,29) = 5.34$, $p = 0.028$). The effect of NUMBER OF OBJECTS was larger for the low prägnanz condition.

7.3. Discussion

According to our hypothesis, when the parts are not perceived as separated parts of a single object, lock-and-key matching is more difficult, and therefore the translation two-object condition becomes harder than the translation one-object condition. This would say something about the nature of the lock-and-key matching process. We did not confirm the pattern of the interaction in Fig. 4B by ANOVA, but did using the Wilcoxon test.

Is the weakness of this effect due to individual differences? We looked at individual data, and individual error rates, and found that performance varies considerably. For some participants PRÄGNANZ made no difference, and they showed the crossover interaction we reported in Experiments 1 and 2. For others, the crossover interaction was absent in both the high and low prägnanz conditions. For a few subjects, we observed the predicted effect of PRÄGNANZ was as predicted. Perhaps lock-and-key matching is a strategy that people can choose to use. This would make this strategy a higher cognitive process compared to, for example, the one-object advantage for reflection.

8. Experiment 4a

In Experiment 3 we found that the regularity of outer contours (PRÄGNANZ) did not significantly alter the interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS. We decided to manipulate prägnanz in a different way, this time instead of trying to make the unified object less regular we did the opposite and we made the two outside objects look more regular. That is, we increased the prägnanz of the outside objects to make the lock-and-key matching weaker. The underlying hypothesis is the same: parts

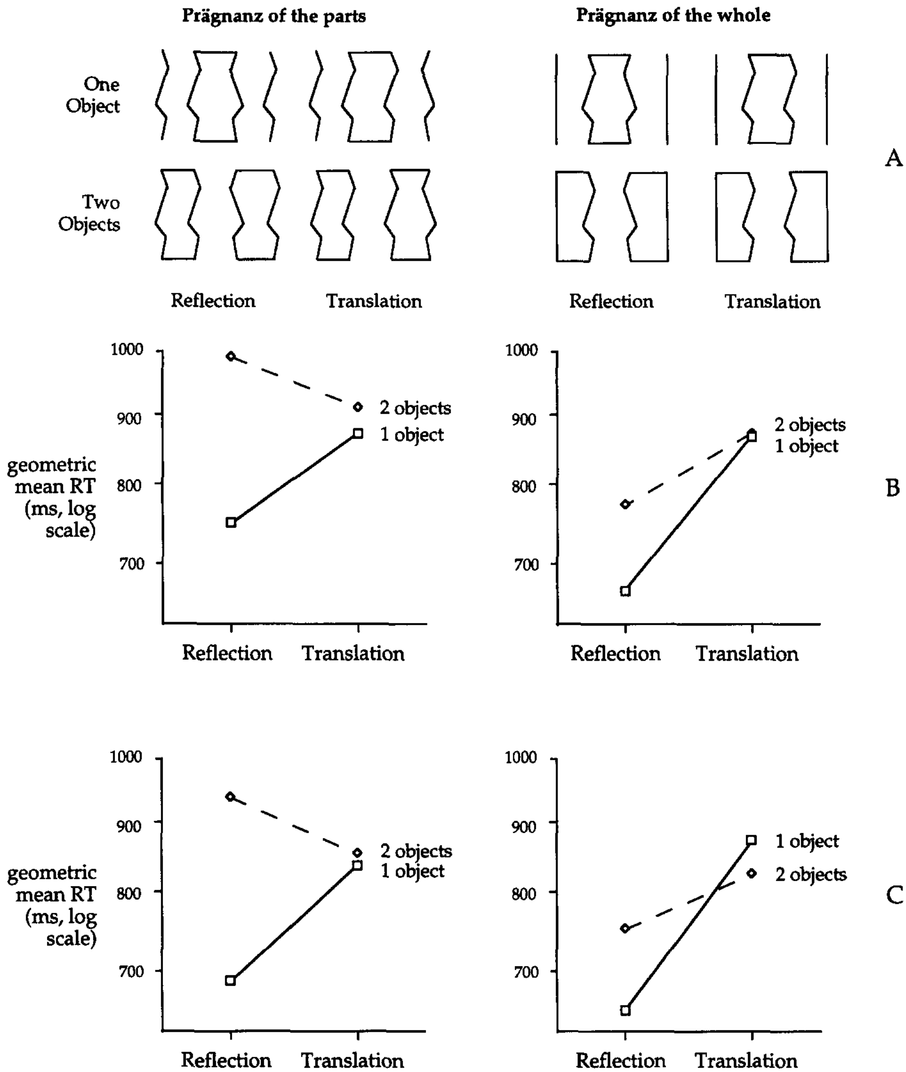


Fig. 5. (A) Line drawings used in Experiment 4a. Compare the outside contours used here with those in Fig. 4. Now the outside line are reflections and translation of the inside contours. Reflection is here drawn on the right side but was randomly on the right or on the left in the experiment. (B) Geometric means of reaction time in ms for Experiment 4a. (C) Geometric means of reaction time in ms for Experiment 4b.

that do not appear to be pieces of an original single object will not lead to an advantage for detection of translation over detection of reflection.

The new stimuli are described in panel A of Fig. 5. Again, these drawings are not exactly those used but they serve the purpose of showing to the reader the effect of the new manipulation. In the experiment new contours were generated for each trial. We call the two conditions *prägnanz of the parts* and *prägnanz of the whole*.

8.1. Method

8.1.1. Subjects

Eleven subjects participated. They were undergraduate or graduate students at the University of Virginia. All subjects had normal or corrected-to-normal vision. They were naive with respect to the hypotheses.

8.1.2. Apparatus and stimuli

The apparatus and the stimuli were identical to Experiment 3, except that the PRÄGNANZ conditions were now those of Fig. 5A.

8.1.3. Design and procedure

We created three within-subjects variables in a factorial design: TYPE OF SYMMETRY (reflection and translation), NUMBER OF OBJECTS (one and two), and PRÄGNANZ (parts and whole), for a total of eight distinct conditions. Every subject saw 4 blocks of 216 trials (with two rest breaks per block). Prägnanz of the parts and prägnanz of the whole were separated in blocks PWPW for half of the subjects and in blocks WPWP for the other half.

8.2. Results and discussion

We used the same data censoring and transformation as we did in Experiment 1. The overall error rate was 7.1%.

8.2.1. We found a three-way interaction between type of symmetry, number of objects, and prägnanz

Results for the three-way interaction of the geometric means are plotted in Fig. 5B. A repeated measures ANOVA confirmed the three-way interaction between TYPE OF SYMMETRY, NUMBER OF OBJECTS, and PRÄGNANZ ($F(1,10) = 10.28$, $p = 0.0094$).

Planned Wilcoxon matched-pair signed-rank comparisons were performed on the conditions of Fig. 5B. For the prägnanz of the parts stimuli: for reflection, one-object stimuli were responded to faster than two-object stimuli ($N = 11$, $T = 0$, $p = 0.0017$); for translation, one-object stimuli and two-object stimuli did not differ ($N = 11$, $T = 23$, $p = 0.19$). For the prägnanz of the whole stimuli: for reflection, one-object stimuli were responded to faster than two-object stimuli ($N = 11$, $T = 2$, $p = 0.0029$); for translation, two-object stimuli and one-object stimuli did not differ ($N = 11$, $T = 28$, $p = 0.33$).

8.2.2. Other effects

The ANOVA confirmed main effects of TYPE OF SYMMETRY ($F(1,10) = 15.52$, $p = 0.0028$), and NUMBER OF OBJECTS ($F(1,10) = 28.04$, $p = 0.00035$). Consistent with Experiment 3, observers responded to reflection stimuli 103 ms faster than to translation stimuli, and to one-object stimuli 99 ms faster than to two-objects stimuli.

The analysis also showed interactions between TYPE OF SYMMETRY and NUMBER OF OBJECTS ($F(1,10) = 16.34$, $p = 0.0024$), between TYPE OF SYMMETRY and PRÄGNANZ ($F(1,10) = 40.84$, $p = 0.000082$), and between PRÄGNANZ and NUMBER OF OBJECTS ($F(1,10) = 16.34$, $p = 0.0024$).

8.3. Discussion

Fig. 5B shows that this time PRÄGNANZ had an effect in changing the interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS, as demonstrated by the three-way interaction. For our hypothesis, the most interesting condition is the translation for two objects, responses to this condition were faster in the prägnanz of the whole condition compared to the prägnanz of the parts condition. However, a similar and larger effect is present for reflection. Possibly, the fact that a regular object was not produced by a lock-and-key matching made the comparison of the two parts more difficult. It is also possible that we made the detection of reflectional symmetry difficult by introducing symmetry into the outside objects. That is, the effect may not as much be a result of the lack of prägnanz of the whole but a result of an increased prägnanz of the parts. The result for prägnanz of the parts is complicated by the fact that, once the two parts are considered united the new object has a translation of the outer contours for reflection, whereas the new object has a reflection of the outer contours for translation. It is possible that we are seeing an asymmetry in that the translation may interfere more with the detection of reflection than vice versa.

9. Experiment 4b

In Experiment 4a we found that the regularity of outer contours (prägnanz) did alter the interaction between TYPE OF SYMMETRY and NUMBER OF OBJECTS. The interpretation of this finding was made difficult by the fact that response time was longer for the condition where extra symmetry information is present. Experiment 4b is a control for Experiment 4a, and the only difference between the two is the fact that now the PRÄGNANZ conditions are intermixed in the same block. Instead, the NUMBER OF OBJECTS conditions are now in separate blocks.

9.1. Method

9.1.1. Subjects

Ten subjects participated. They were undergraduate students at the University of Virginia and were fulfilling a requirement for an introductory psychology course. All subjects had normal or corrected-to-normal vision. They were naive with respect to the hypotheses.

9.1.2. Apparatus and stimuli

The apparatus and the stimuli were identical to Experiment 4a.

9.1.3. Design and procedure

We created three within-subjects variables in a factorial design: TYPE OF SYMMETRY (reflection and translation), NUMBER OF OBJECTS (one and two), and PRÄGNANZ (parts and whole), for a total of eight distinct conditions. Every subject saw 4 blocks of 216 trials (with two rest breaks per block). The one-object and the two-object conditions were separated in blocks OTOT for half of the subjects and in blocks TOTO for the other half.

9.2. Results and discussion

We used the same data censoring and transformation as we did in Experiment 1. The overall error rate was 11.3%.

9.2.1. Three-way interaction between type of symmetry, number of objects, and prägnanz

Results for the three-way interaction are plotted in Fig. 5C. The similarity between the pattern of the interaction in Experiment 4a and Experiment 4b is strong. The effect of prägnanz of the parts was that, for both translation and reflection, the two-object comparison was made slower with respect to the prägnanz of the whole condition. But reflection shows a larger effect. A repeated measures ANOVA did not confirm a three-way interaction ($F(1,9) = 1.297$), but only an interaction TYPE OF SYMMETRY and NUMBER OF OBJECTS ($F(1,9) = 44.11$, $p = 0.000095$).

We performed planned Wilcoxon matched-pair signed-rank comparisons on the conditions of Fig. 5C. For prägnanz of the parts stimuli: for reflection, one-object stimuli were responded to faster than two-object stimuli ($N = 10$, $T = 5$, $p = 0.011$); for translation, one-object stimuli and two-object stimuli did not differ ($N = 10$, $T = 26$, $p = 0.44$). For prägnanz of the whole stimuli: for reflection, one-object stimuli were responded to faster than two-object stimuli ($N = 10$, $T = 5$, $p = 0.011$); for translation, two-object stimuli and one-object stimuli did not differ ($N = 10$, $T = 13$, $p = 0.070$).

Although the three-way interaction did not reach significance, overall Experiment 4b led to results consistent with Experiment 4a, as can be seen by comparing Panels B and C of Fig. 5.

9.2.2. Other effects

A repeated measures ANOVA confirms a main effect of TYPE OF SYMMETRY ($F(1,9) = 21.74$, $p = 0.0012$), responses to reflection were 100 ms faster than responses to translation. We found also an interaction TYPE OF SYMMETRY and PRÄGNANZ ($F(1,9) = 10.96$, $p = 0.0091$), and an interaction NUMBER OF OBJECTS and PRÄGNANZ ($F(1,9) = 5.95$, $p = 0.037$).

9.2.3. Analysis of the errors

Because the error rate was relatively high, above 10%, we tested the logit of the percentage of correct responses in a second ANOVA with the same design as the ANOVA for response time. It showed a main effect of TYPE OF SYMMETRY ($F(1,9) = 8.934$, $p = 0.015$), more errors were made for translation than for reflection, and of PRÄGNANZ ($F(1,9) = 8.208$, $p = 0.019$), more errors were made for the prägnanz of the parts condition. The ANOVA also showed an interaction TYPE OF SYMMETRY and NUMBER OF OBJECTS ($F(1,9) = 34.649$, $p = 0.0001$), and an interaction NUMBER OF OBJECTS and PRÄGNANZ ($F(1,9) = 19.219$, $p = 0.002$). The direction of the differences was the same as that of the response time, and a plot of the means shows the same pattern of Fig. 5C.

10. General discussion

Experiment 1 showed, using line drawings, that detection of reflection between contours was faster when the contours belong to a single object, whereas detection of translation was faster when the contours belong to two objects. This interaction did not depend upon two different strategies adopted by the subjects to detect reflection or translation. At least in so far that the mixing of trials for reflection and translation did not hinder the effect. Moreover, the effect did not depend on local polarity changes.

If the difference between one and two objects is the results of an additional cost for processing two objects, why is this cost not present for translation? It was proposed that detection of translation can be easier when a lock-and-key match is possible. We tested this hypothesis in Experiment 2, 3, and 4. A mental transformation might translate the contours in the plane until they lock into one another. Assuming that the contours are boundaries of rigid objects, then they should stop when they touch. In other words, a match that can be performed on the plane (lock-and-key) should be easier than one that requires an overlap. However, Experiment 2a and 2b failed in finding support for this hypothesis by comparing jigsaw matching and simple lock-and-key matching. It is fair to observe that these experiments falsify only a specific and strong hypothesis about lock-and-key in which a match is performed by virtually translating the two rigid objects in the plane.

The fact that the crossover interaction found in Experiment 1 was weaker in the lock-and-key condition of Experiments 2a and 2b is not accounted for by the explanations discussed so far, and it is contrary to our original hypothesis. A possible explanation is that the contours used for translation in our experiments are difficult to match because they are too trim and regular on their own. In other words, using the Lock-and-key stimuli of Experiment 2 we altered the prägnanz of the whole so that the two parts do not have the jagged appearance of pieces coming from the rupture of a single original object. Leyton (1992) has proposed that perception is a process of reconstructing the history of an object. If this is so, maybe the lock-and-key matching can take place only when the two pieces appear as parts that once belonged together.

Experiment 3 introduced a new variable to test the idea that the lock-and-key matching process only occurs between parts that are phenomenally pieces of an original single object. Of course interpretation of the effect of the variable called prägnanz in Experiment 3 relies on a phenomenal observation that we have not studied directly. Looking at Fig. 4A you need to appreciate how the jagged outer contours change the overall appearance of the display. Fig. 4B shows that this effect on the prägnanz of the figure made it more difficult to identify the translation between two objects. This conclusion is supported by statistical tests, but interpretation of the results is not straightforward, mostly because of the high inter subjects variability. We take this variability as evidence that people can organize a display differently and this affects in turn their ability to detect symmetry. In this sense this is evidence that higher perceptual or cognitive processes are affecting detection of translation. An example of this would be the use of global or local strategies by the observers. The effect of the context (outside lines) should be higher for individuals who adopt a more global strategy.

Experiment 4 is saying something more specific about what kind of perceptual organization can affect detection of symmetry. In this experiment the presence of regular objects embedding some of the contours to be judged made a large difference, particularly for detection of reflection. This is an important difference between the results of Experiment 3 and 4. In Experiment 3 detection of reflection was always faster than detection of translation. In Experiment 4 instead, when a contour belongs to a symmetric figure, it is hard to see that it is also related to another contour in a different figure, and under these circumstances it is easier to detect translation that reflection. A general effect of interference is not sufficient to explain the differential effect that this interference has on reflection and translation.

It is important to note how interesting this finding is. Perceptual organization, that depends on the regularity of a figure, can lead to different processing of the symmetry information, to the point of erasing a lock-and-key advantage for translation that was previously found to be quite robust. We have introduced in this paper a few manipulations of the perceptual organization of a display to study the interaction of symmetry perception with other perceptual factors. At least one of these manipulations, namely the fact that a contour is placed within a connected object that is itself symmetrical led to a slower response for the detection of reflection. A possible explanation is that reflection is searched for inside objects, and when found the system stops analyzing the relationship between separate objects. This is consistent with the ecological difference between reflection and translation, the first being more important for defining an object and the second for finding the relationship between different parts of an originally unitary object.

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References

Baylis, G.C. and J. Driver, 1993. Visual attention and objects: Evidence for hierarchical coding of location. Journal of Experimental Psychology: Human Perception and Performance 19(3), 451–470.

Baylis, G.C. and J. Driver, 1994. Parallel computation of symmetry but not repetition within visual shapes. Visual Cognition 1, 377–400.

Baylis, G.C. and J. Driver, 1995. Obligatory edge assignment in vision: The role of figure and part segmentation in symmetry detection. Journal of Experimental Psychology: Human Perception and Performance 21, 1323–1342.

Bertamini, M., M. Bhalla, J. Friedenberg, J. Joseph and M. Kubovy, 1993, June. Symmetry and perceptual organization. Paper presented at the American Psychological Society, Chicago, IL.

Biederman, I., 1987. Recognition by components: A theory of human image understanding. Psychological Review 94(2), 115–147.

Hoffman, D.D. and D.A. Richards, 1984. Parts of recognition. Cognition 18, 65–96.

Jenkins, B., 1983a. Component processes in the perception of bilaterally symmetric dot textures. Perception and Psychophysics 34(5), 433–440.

Jenkins, B., 1983b. Spatial limits to the detection of transpositional symmetry in dynamic dot textures. Journal of Experimental Psychology: Human Perception and Performance 9, 258–269.

Kanizsa, G., 1979. Organization in vision: Essays on Gestalt perception. New York: Praeger.

Leyton, M., 1992. Symmetry, causality, mind. Cambridge, MA: MIT Press.

Mach, E., 1886/1995. The analysis of sensations. New York: Dover.

Marr, D. and H.L. Nishihara, 1978. Representation and recognition of the spatial organization of three-dimensional shapes. Proceedings of the Royal Society, 200B, 269–294.

Palmer, S.E. and K. Hemenway, 1978. Orientation and symmetry: Effects of multiple, rotational and near symmetries. Journal of Experimental Psychology: Human Perception and Performance 4(4), 691–702.

Palmer, S.E. and I. Rock, 1994. Rethinking perceptual organization: The role of uniform connectedness. Psychonomic Bulletin and Review 1, 29–55.

Rock, I., 1983. The logic of perception. Cambridge, MA: MIT Press.

Rock, I., D. Wheeler and L. Tudor, 1989. Can we imagine how objects look from other viewpoints? Cognitive Psychology 21, 185–210.

Shepard, R.N., 1994. Perceptual-cognitive universals as reflections of the world. Psychonomic Bulletin and Review 1(1), 2–28.

Ulrich, R. and J. Miller, 1993. Information processing models generating lognormally distributed reaction times. Journal of Mathematical Psychology 37, 513–525.

Wagemans, J., L. van Gool, V. Swinnen and J. van Horebeek, 1993. Higher-order structure in regularity detection. Vision Research 33, 1067–1088.