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Sensitivity to reflection and translation is modulated by objectness

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Abstract. The salience of a transformation between a pair of contours depends on the type of transformation (eg a reflection or a translation) and also on figure – ground organisation. Reflection is most salient when both contours belong to the same surface, and translation is most salient when they do not connect a surface. These findings are based on reaction time (RT). Here I replicate and extend them by measuring both RT and sensitivity. The figure – ground relations were changed unambiguously by using stereograms. I compared reflection and translation when they were present within a surface or across surfaces (experiment 1), and within an object or a hole (experiments 2 – 4). Holes are interesting because they are not objects, but their presence does not increase the number of total objects in the scene. The within-surface advantage for reflection was present in all experiments. There was a between-surface advantage for translation in experiment 1 but there was no hole advantage for translation in experiments 2 – 4. Thus the effect of context, ie objectness, on detection of regularity is a robust and general phenomenon present in every experiment, but the type of interaction differs for reflection and translation.

1 Introduction

Transformations that preserve metric structure are called isometries. In the plane, these are reflection, translation, rotation, and glide reflection. An isosceles triangle is an example of reflection because there is an axis around which the shape can be reflected. A star is an example of rotation because there is a point around which one can rotate the shape and map it onto itself. Isometric transformations can therefore create symmetric patterns, which are important in art and have also attracted much interest within the visual-perception literature (Tyler 1996; Wagemans 1997).

One empirical fact about human observers that has been noted more than a century ago (Mach 1885/1914) is that bilateral symmetry, especially around a vertical axis, is more salient than a repetition. I will refer to this regularity as reflection instead of bilateral symmetry, because the focus of this paper is on the transformations themselves rather than on symmetry. A reflection is even more salient when two reflected contours are part of a closed region, ie an object. The importance of holistic processing on perception of symmetry was first noted by Corballis and Roldan (1974). It is worth describing their findings in some detail.

Corballis and Roldan used simple patterns that were either symmetrical about, or repeated across, a vertical axis (hereforth reflection and translation). There were two instruction conditions: in one observers were to report whether the pattern was "mirror" or "same", in another they were to report whether the pattern was "symmetrical" or "asymmetrical". With dot patterns, reflection was always responded to faster than translation when the dots were close together, but the opposite was true when the dots were farther apart. With even simpler stimuli made up of arrows there was a difference depending on the instructions. "Same" responses were faster than "mirror" but "asymmetrical" responses were marginally slower than "symmetrical". In the case of arrows, the distance between the pair did not make a difference. Corballis and Roldan (1974) concluded that, if the patterns are perceived holistically, reflection is more salient than translation, but, if they are perceived as two objects, then translation is responded to faster than reflection.

Later studies have confirmed and extended this pattern of results. A general advantage has been proposed for attending to a single object rather than across objects (Duncan 1984; Baylis and Driver 1994; but see Davis and Holmes 2005). This one-object advantage does not exist when the regularity to be detected is a translation (Bertamini et al 1993; Baylis and Driver 1995). It is likely that the convexities and concavities on the opposite sides of an object are an important factor (Baylis and Driver 1994). This type of match is present for objects with reflected contours, but not for objects with translated contours. Csatho et al (2003) have pointed out that within an object a translation creates an anti-translation or anti-repetition. As my terminology refers to the regularity of the contours rather than that of the surfaces, I will retain the term translation but it is worth keeping in mind that the effects of context (closure) that we are discussing may depend on the way surfaces are perceived. However, there is a cost for detecting translation within one object compared to a translation across two objects, and this is not easily explained because, in the case of translated contours, two facing objects have a mismatch in terms of convexities, just as in the case of a closed object. The basic pattern of interest is an interaction between type of regularity (reflection and translation) and number of objects (one and two). Baylis and Driver (1994) and Bertamini et al (1997) have suggested that the one-object cost for translation is really an advantage for finding a lock-and-key match between the two objects.

Perhaps this lock-and-key matching is a type of mental transformation, akin to mental rotation. However, there are some difficulties with the lock-and-key explanation.

(i) Bertamini et al (1997) have compared translated contours that slide into a match along a plane with translated contours that looked like jigsaw pieces and therefore could not slide into place within a plane. That is, a translation confined to the plane was not possible without some overlapping of the contours. The interaction was present in both cases.

(ii) Treder and van der Helm (2007) have found that, unlike reflection, the detection of repetition does not depend on structural correspondences within a single depth plane.

(iii) Bertamini et al (2002) have found the one-object cost also for detection of rotated contours. In some cases the pair of rotated contours was joined by a surface and in other cases it was separated by an open space. For instance, imagine comparing the two sides forming the mouth of a pacman shape. The interaction was present, even though there was always the same number of objects (eg a single pacman shape).

(iv) Bertamini et al (2002) interviewed participants and found that the strength of the interaction effect did not correlate with whether the observers reported adopting mental transformation as a strategy.

These results highlight the fact that more work is necessary to understand the nature of the interaction between the type of regularity and number of objects. Treder and van der Helm (2007) proposed that symmetry is a cue for the presence of one object, whereas repetition is a cue for the presence of multiple objects. In other words a close association exists between the different types of regularities and the context in which they are encountered. Given that repetition is found mainly when multiple objects are present, this is the condition in which performance is best. This link may have been internalised by the system so as not to depend on previous experience of an individual.

A recent paper by Koning and Wagemans (2009) addressed directly the origin of the interaction between type of regularity and context. The stimuli were a pair of contours belonging to either a single object or two objects. The objects were rotated in depth, so that it was difficult to perform a matching strategy based on simple translation of the 2-D contours. Reflection was never detected more easily than repetition in the two-objects displays. Koning and Wagemans concluded that structural coding, not a matching strategy, underlies the one-object advantage for reflection and the two-objects advantage for repetition (translation).

Although I have used the term "lock-and-key" in the past (Bertamini et al 1997), I do agree with Treder and van der Helm (2007), and Koning and Wagemans (2009) that an explanation has to be sought in terms of structural coding rather than a matching strategy. This is supported by the pieces of circumstantial evidence cited above. However, I think it is far from clear that the key variable is the number of objects, as opposed to the nature of the difference between a surface and a gap. In the case of a surface, the closure of the contours affects how the object is coded, including structural descriptors such as its axis of elongation (Kovács and Julesz 1993), and these processes may not apply to ground regions. In terms of the existing evidence, Koning and Wagemans's (2009) claim that the key factor is the number of objects explains only the data about translation, and fails to generalise to the results about rotational symmetry in which an interaction is present with only a single object (Bertamini et al 2002).

In their study, Treder and van der Helm (2007) used stereograms to manipulate the depth plane of dots. In this paper I use stereograms to manipulate figure–ground (Bertamini and Mosca 2004; Bertamini and Farrant 2006). This not only makes figure–ground relations unambiguous; in addition it allows new manipulations, in particular the introduction of closed regions of ground, namely holes. The advantage of using holes is the fact that a hole presents a gap between two contours while the number of objects in the scene does not change (Bertamini 2006).

Another novelty in this paper is the fact that I tested whether the interaction described above for response time extends to other measures of performance, and in particular a measure of sensitivity. This is important because if this interaction emerges from a fundamental difference in structural coding for reflection and translation, then one ought to expect a difference in sensitivity. There have been studies on the efficiency of symmetry detection, for instance the classic paper by Barlow and Reeves (1979), but with respect to the effect of context discussed above the evidence is entirely based on reaction-time (RT) data. There is also some skepticism amongst vision scientists about conclusions drawn from RT data (Watt 1991). Without entering the merit of such debate, it is nevertheless another reason why a comparison between RT and signal-detection analyses is interesting.

2 Experiment 1: Sensitivity to reflection and translation in context

This experiment tests the interaction between type of transformation (reflection and translation) and the context in which the contours are embedded. This context refers to the number of surfaces (one and two). Instead of using luminance edges, shapes were only defined within random-dot stereograms (RDSs). This was done to ensure unambiguous figural status. Unlike a stereogram with luminance edges, in an RDS shape information is not available before depth stratification. Moreover, all surfaces in an RDS are identical in colour and texture. A constrained random-walk algorithm was used to generate the contours so that the same contours were never used in more than one trial. Importantly, unlike previous work, I analysed sensitivity by computing d' values instead of analysing response time. Presentation time was chosen after piloting so as to make the task hard—and therefore generate hits as well as false alarms—but not impossible.

2.1 *Method*

2.1.1 *Participants.* Fourteen students at the University of Liverpool participated. Their vision was normal or corrected to normal. Before the experiment started, their stereovision was tested with the TNO stereo test.

2.1.2 *Stimuli and design.* The factors were transformation (reflection and translation), type of object (within a single surface or between surfaces), and presentation time.

They were factorially combined in a within-subjects design. For reflection, the presentation times were 166 or 333 ms. For translation, the times were 333 or 500 ms. This was done because detection of translation is harder than detection of reflection. Every participant took part in two blocks of trials. In one block the task was to detect a reflection of the contours, in the other the task was to detect a translation. Reflection was in the first block for half of the participants and the reverse order for the other half.

Stimuli were generated on a Macintosh computer (Pelli 1997), and presented on a Sony F500T9 monitor with a resolution of 1280 by 1024 pixels at 120 Hz. Figure 1 illustrates the stimuli. The width of the square background was 15 cm. The stimulus itself was 3 cm high and 4.5 cm wide. There were 6 steps equally spaced in the vertical dimension (9 pixels) and with a random horizontal offset chosen within a range between -9 and $+9$ pixels. In the reflection condition, the left and the right contours were identical under a reflection; in the translation condition, they were identical under a translation. Irregular contours were generated by the same algorithm as the regular contours, but the left and the right sides were generated independently. New stimuli were generated for each trial; therefore there was no possibility that the observers could become familiar with one specific shape.

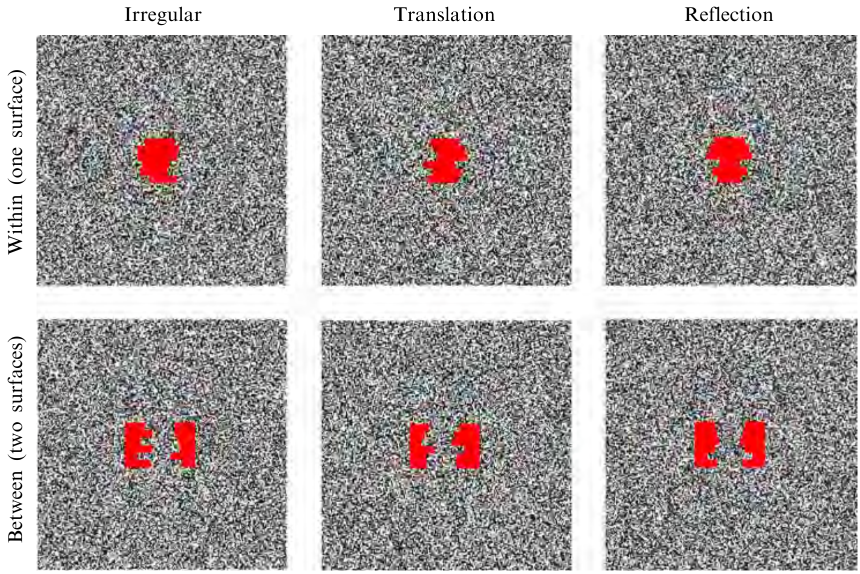

Figure 1. [In colour online, see http://dx.doi.org/10.1068/p6393] Examples of the stimuli from the 4 conditions of experiment 1. New stimuli were generated on each trial, and therefore what defined the condition (eg reflection) was only the relationship between the contours. These stimuli accurately describe the first half of the practice trials. In the second half of the practice and in the experiment the foreground region was defined only by disparity (random-dot stereogram).

Each observer sat in a dimly illuminated room at a distance of approximately 57 cm from the monitor. There was always an equal number of trials in which the contours were regular and irregular. Observers were instructed to respond with a key to the presence of a regular contour (reflection in one block or translation in the other) and another key to the absence of regularity, using a USB game pad.

Each block started with two practice sessions of 15 trials each. In the first practice the surfaces of the objects were coloured solid red. This was done to familiarise the observers with the types of shapes used. The second practice was identical to the actual experiment and all surfaces had the same random-dot pattern, so that shape information was only available after the stereogram had been processed and depth-order unambiguously established.

After the practice, each block contained 400 trials. The trials were presented in rapid succession, but after every 80 trials there was a pause (4 pauses in total) and the observer was allowed time to rest. The subsequent restart was self-paced.

2.2 *Results and discussion*

The factors analysed were the type of regularity, the type of objects, and the presentation time. I computed hits and false alarms for each combination of these factors and from these I computed d' values. This measure of sensitivity was entered in a repeated-measures ANOVA. To perform a single analysis I treated presentation time as having two levels—short and long presentation. This was indeed the case, although the values were different for reflection and translation. To compare performance at the same value of presentation time one could compare the long presentation for translation with the short presentation for reflection in figure 2. As expected the overall level of performance diverged greatly for the two transformations.

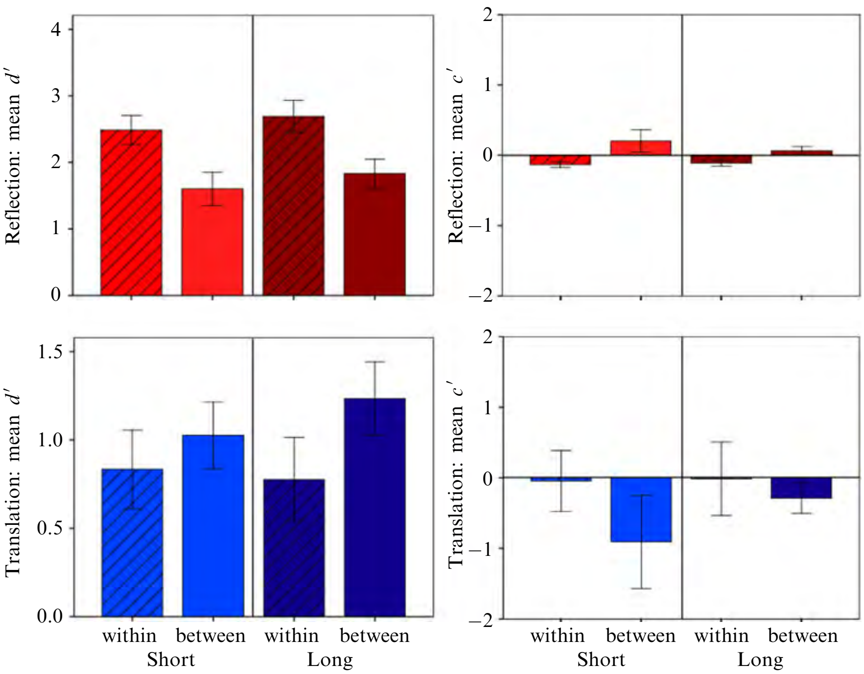

Figure 2. [In colour online] Results from experiment 1. The error bars show the standard error of the mean. These error bars are appropriate for between-subjects comparisons but not for the within-subjects comparisons (Loftus and Masson 1994).

Sensitivity was higher for reflection than for translation ($F_{1,13} = 34.67$, $p < 0.01$), and when presentation time was longer, but only marginally ($F_{1,13} = 4.65$, $p = 0.05$). Sensitivity was also higher for the within-object condition compared to the between-objects condition ($F_{1,13} = 12.16$, $p < 0.01$).

The only other significant effect was the interaction between type of transformation and type of object ($F_{1,13} = 30.11$, $p < 0.01$). As predicted, figure 2 shows that sensitivity was higher for one object (within) in the case of reflection, but for two objects (between) in the case of translation. To confirm this pattern, two pre-planned t-tests were performed comparing one and two objects separately for reflection and for translation. Both were significant: for reflection $t_{13} = -6.81$, $p < 0.01$, for translation $t_{13} = 2.60$, $p < 0.05$. It appears therefore that there were both a single-object advantage for reflection and a single-object cost for translation. Obviously this could also be described as a between-objects advantage for translation.

In addition to sensitivity, I computed an index of bias to see if observers had a greater bias to say that the shape was regular in one condition or another. This index, c, has the same range as d' but is centred on zero. Because of the variability in sensitivity between participants the value of c was standardised ($c' = c/d'$) (Macmillan and Creelman 1991). I performed an ANOVA using c' as the dependent variable and with the same factors as the previous ANOVA. There were no significant main effects or interactions. The mean values are shown in figure 2.

Our participants were not asked to respond as quickly as possible. Nevertheless, the computer did record their response time and it is interesting to analyse these data. I performed a repeated-measures ANOVA with type of transformation and number of objects as factors. Type of transformation was significant ($F_{1,13} = 10.49$, $p < 0.01$), but number of objects was not significant ($F_{1,13} = 1.78$, ns). More importantly, the interaction was significant ($F_{1,13} = 11.88$, $p < 0.01$). The pattern of the interaction was consistent with the pattern for sensitivity: observers were slower at responding for a harder discrimination.

The results confirmed the prediction: a reflection is more easily perceived within an object, which in this experiment means that both contours belong to the same surface; translation, on the other hand, is more easily perceived when the contours belong to separate surfaces.

3 Experiment 2: Objects and holes

In experiment 1 I analysed sensitivity and found an interaction between type of transformation and type of separation between the contours. Previous studies had reported a similar interaction in terms of RT. Experiment 2 introduced a new manipulation. Given a closed contour, it is possible that such region is perceived as a figure (a surface) or as ground (a gap in a surface, ie a hole). This manipulation would be difficult without the use of RDSs, because closed regions tend to be perceived as figures (Bertamini 2006). Within an RDS one can be confident that the figure–ground relations are those specified by the disparity. Even if stereograms may require some time to be fully and unambiguously perceived, the fact that no shape information is available until the stereo information has been processed insures that responses cannot be initiated before stereo fusion.

Two versions of this experiment were run to compare RT (experiment 2a) and d' values (experiment 2b). The only difference in the method was that in the case of the RT experiment the shape remained on the screen until a response was produced and participants were asked to respond as quickly as possible.

3.1 *Method*

3.1.1 *Participants.* Twelve students at the University of Liverpool participated in experiment 2a and fourteen in experiment 2b. Their vision was normal or corrected to normal. Before the experiment started their stereovision was tested with the TNO stereo test.

3.1.2 *Stimuli and design.* For experiment 2a the factors were transformation (reflection and translation), and type of object (object or hole). For experiment 2b, the factors were transformation (reflection and translation), type of object (object or hole), and presentation time. For reflection, the presentation times were 166 or 333 ms. For translation, the times were 333 or 500 ms. The hardware and the procedure were the same as in experiment 1. Stimuli are illustrated in figure 3. The stimulus containing the hole was a square, 4.5 cm wide.

Each participant saw two balanced blocks of trial, one for reflection and one for translation. For experiment 2a, the total number of trials was 720 per observer, and for experiment 2b it was 800.

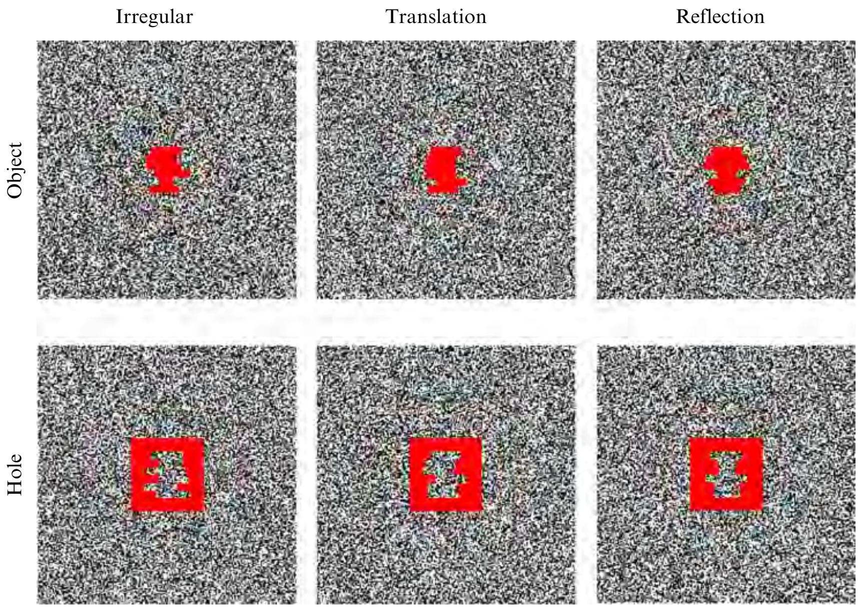

Figure 3. [In colour online] Examples of the stimuli of experiment 2. New stimuli were generated on each trial. These stimuli accurately describe the first half of the practice trials. In the second half of the practice and in the experiment the foreground region was defined only by disparity (random-dot stereogram).

3.2 *Results and discussion*

3.2.1 *Reaction-time data.* The factors analysed were the type of regularity and the type of stimulus. Two participants were excluded because of high error rates. A repeated-measures ANOVA on log transformed RT confirmed that responses were faster for reflection than for translation ($F_{1,11} = 59.20$, $p < 0.01$), and for objects compared to holes ($F_{1,11} = 14.66$, $p < 0.01$). There was also an interaction between the two ($F_{1,11} = 8.86$, $p < 0.05$). Two pre-planned t-tests were performed, comparing objects and holes separately for reflection and for translation. As can be seen in figure 4, responses were faster to objects compared to holes in the case of reflection ($t_{11} = 6.66$, $p < 0.01$), but not in the case of translation ($t_{11} = 0.38$, ns). The same pattern was present for errors, with a difference in the case of reflection ($t_{11} = 3.77$, $p < 0.01$) but not in the case of translation ($t_{11} = 1.45$, ns). The average error rate was 10%.

3.2.2 *Sensitivity.* The factors analysed were the type of regularity, the type of stimulus, and the presentation time. I computed hits and false alarms for each combination of these factors and from these I computed d' values. In a repeated-measures ANOVA, presentation time was treated as having two levels: short and long. Sensitivity was higher for reflection than for translation ($F_{1,11} = 126.25$, $p < 0.01$), when presentation time was longer ($F_{1,11} = 11.83$, $p < 0.01$), and for objects compared to holes ($F_{1,11} = 40.10$, $p < 0.01$).

Importantly, the only significant interaction was between type of transformation and type of stimulus ($F_{1,11} = 53.62$, $p < 0.01$). Two pre-planned t-tests were performed comparing objects and holes separately for reflection and for translation. Figure 4 shows that sensitivity was higher in the object conditions in the case of reflection ($t_{11} = -12.29$, $p < 0.01$), but not in the case of translation ($t_{11} = -1.10$, ns). Therefore there was an object advantage for reflection but no object cost for translation.

In addition to sensitivity (as measured by d') I also computed a measure of bias to see if participants had a greater bias to respond that the object was regular in the

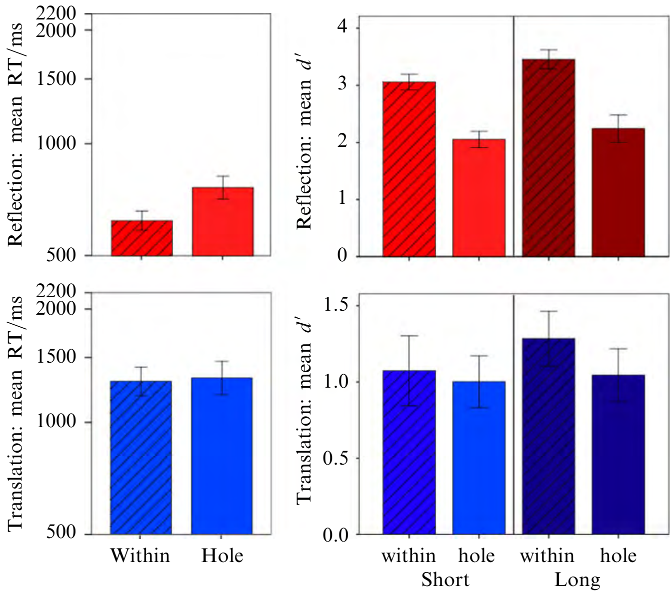

Figure 4. [In colour online] Results from experiment 2. The error bars show the standard error of the mean.

object or in the hole condition ($c' = c/d'$), and performed an ANOVA with the same factors as in the previous ANOVA. There was no significant effect or interaction. Therefore, a measure of sensitivity, but not a measure of bias, mirrors RT performance.

In discussing the results of experiment 2 it is useful to consider reflection and translation separately. For reflection there is a clear advantage when the task is to compare contours across the surface of an object. Note that, unlike in experiment 1, a single object is present for both object and hole conditions, so the effect cannot be attributed to the number of objects. However, because a hole needs an object in which to exist, a possible interpretation of this finding is in terms of space-based attention. Perhaps the larger area of the object-with-hole meant that attention had to spread more (eg Brawn and Snowden 2000).

Extra vertical contours are present on the outside of the between-objects condition of experiment 1 and also in the hole condition of experiment 2. These vertical lines have a vertical axis of symmetry and may affect the task of detecting reflection, although, since they are present in both experiments, they cannot explain the difference in results. Experiment 4 tests this aspect of the stimuli.

With respect to translation, no significant difference was found between objects and holes. This is a problem for the interpretation of the results. One might say that perhaps this supports the idea of a lock-and-key strategy, because there is no simple mental transformation that can be applied to the two sides of a hole. However, if it is true that there is a cost for responding to a larger stimulus, as I suggested in the previous paragraph, then one must explain why the hole condition was not harder than the object condition in the case of translation. Perhaps there was a trade-off between different factors. This was the motivation for experiments 3 and 4.

4 Experiment 3: Equal foreground area

I modified the stimuli used in experiment 2 in two ways. First, to equate the total area of the foreground stimulus, a frame was added around the single-object condition. Areas in different trials are the same on average because a constrained algorithm generated the new stimulus on each trial. The new stimuli can be seen in figure 5.

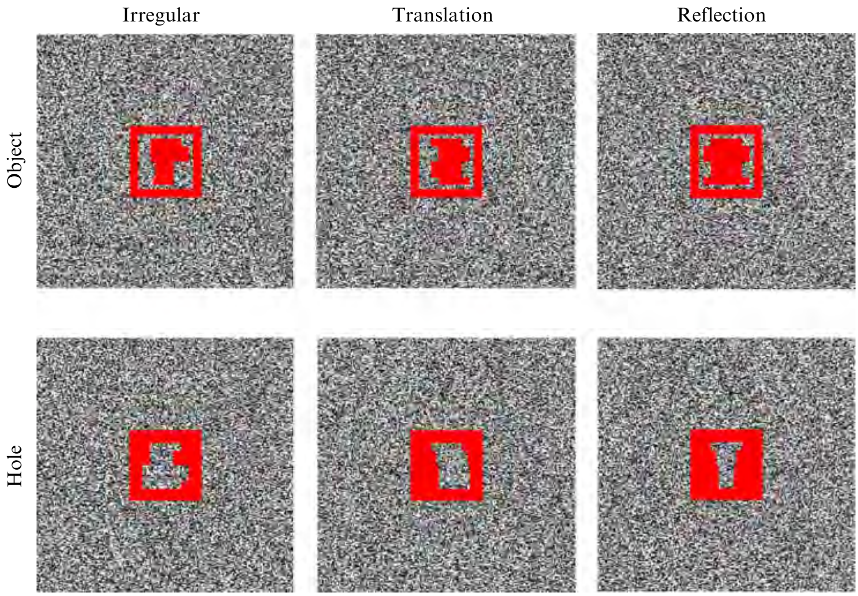

Figure 5. [In colour online] Examples of the stimuli of experiment 3. New stimuli were generated on each trial. These stimuli accurately describe the first half of the practice trials. In the second half of the practice and in the experiment the foreground region was defined only by disparity.

As expected, experiments 1 and 2 show that the detection of contour translation was much more difficult than the detection of contour reflection. To decrease the difference in performance between reflection and translation I reduced the number of possible features of the object. The data from Baylis and Driver (1994) show that performance for translation decreases with an increase in the number of features. In addition to these changes to the stimuli, the design of experiment 3 included only one presentation time (400 ms for translation and 200 ms for reflection) and participants were tested only by using one of the two transformations (either translation or reflection). Therefore there was no risk of any carry-over effect.

The main purpose of experiment 3 was to test whether there is an advantage for holes over objects for translation when using simpler stimuli and matching the foreground area in all stimuli. Data on reflection were collected to have a side-by-side comparison and to replicate the results of experiment 2.

4.1 *Method*

4.1.1 *Participants.* A total of fifty students at the University of Liverpool participated in the different versions of the experiment. For translation, experiment 2a ($N = 13$) tested RT and experiment 2b ($N = 13$) tested sensitivity. For reflection, experiment 2c ($N = 12$) tested RT and experiment 2d ($N = 12$) tested sensitivity. Before the experiment started, participants' stereovision was tested with the TNO stereo test.

4.1.2 *Stimuli and design.* For all experiments the factors were transformation (reflection and translation), and type of object (object or hole). Presentation time was 400 ms for translation and 200 ms for reflection in the versions of the experiments in which d' was measured. Stimuli were on screen until a response for the RT versions. The hardware and the procedure were the same as in experiment 1. Stimuli are illustrated in figure 5. In each session there was a total of 320 trials.

4.2 *Results*

4.2.1 *Reaction time data.* Mean values for RT and for sensitivity can be seen in figure 6. The factors analysed were the type of regularity (between-subjects) and the type of stimulus (within-subjects). A repeated-measures ANOVA on log transformed RT confirmed that responses were faster for reflection than for translation ($F_{1,24} = 33.02$, $p < 0.01$), but not different for objects than for holes ($F_{1,24} = 1.50$, ns). Two pre-planned t-tests were performed comparing objects and holes separately for reflection and for translation. Responses were faster to objects than to holes in the case of reflection ($t_{12} = 2.30$, $p < 0.05$), but not in the case of translation ($t_{12} = -1.25$, ns). Error rate was 9.1% for reflection and 11.6% for translation. In the case of reflection ($t_{12} = 4.36$, $p < 0.01$) and also in the case of translation ($t_{12} = 2.72$, $p < 0.05$) there were more errors for holes than for objects.

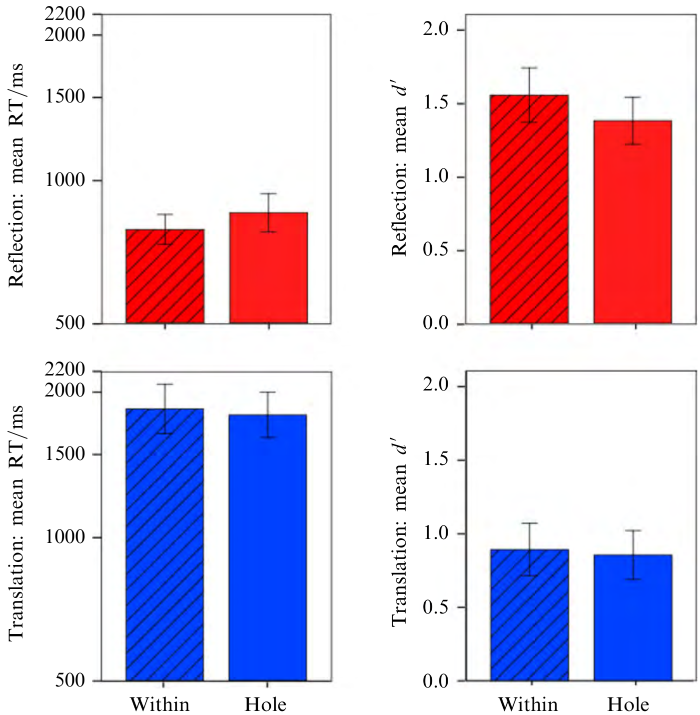

Figure 6. [In colour online] Results from experiment 3. The error bars show the standard error of the mean.

4.2.2 *Sensitivity.* The factors analysed were the type of regularity (between-subjects) and the type of stimulus (within-subjects). A repeated-measures ANOVA on d' values confirmed that sensitivity was higher for reflection than for translation ($F_{1,22} = 25.49$, $p < 0.01$), and for objects than for holes ($F_{1,22} = 5.53$, $p < 0.05$). Two pre-planned t-tests were performed comparing objects and holes separately for reflection and for translation. Sensitivity was higher for objects than for holes in the case of reflection ($t_{11} = 2.57$, $p < 0.05$) but not in the case of translation ($t_{11} = -0.44$, ns).

In addition to sensitivity I also computed a measure of bias ($c' = c/d'$) to compare the object and the hole conditions, and performed another ANOVA. There was no significant effect or interaction. Therefore, as in experiment 2, a measure of sensitivity, but not a measure of bias, mirrors RT performance.

A final comment is necessary about the overall level of performance in experiment 3 compared to experiment 2. For translation this was similar, whilst for reflection it was worse. The expectation was that the task would be easier for translation and equally difficult for reflection, so something in the method or the set of participants hindered performance. In part, this may simply be due to the between-subjects design which meant that there were fewer data per observer, assuming that some improvement over time takes place. A more likely possibility is that the algorithm generating the stimuli may have generated random stimuli that were so simple in terms of number of parts that they may have appeared as roughly regular. If the rejection of the irregular stimuli was harder, then the discrimination task was harder. What is important, however, is that the mean d' values for reflection and translation were more similar to each other in experiment 3 than in experiment 2, as intended.

5 Experiment 4: Same contours

In previous experiments the hole was presented within an object-with-hole, this was a square of arbitrary size. Experiment 3 tried to control for the role of this square by introducing another square in the object condition. In experiment 4 the strategy is different, the conditions are an object in front of a square background and a hole in an object that is identical in size to what was the background in the other condition. Therefore, ignoring depth, the contours present in a stimulus are identical in the object and in the hole conditions. The other parameters for the stimuli were based on the stimuli of experiment 2. Figure 7 illustrates the new stimuli.

Given that in previous experiments no difference was found from the comparison between RT data and d' data, in this final control experiment I only measured reaction times. Results are compared to the reaction times from experiment 2.

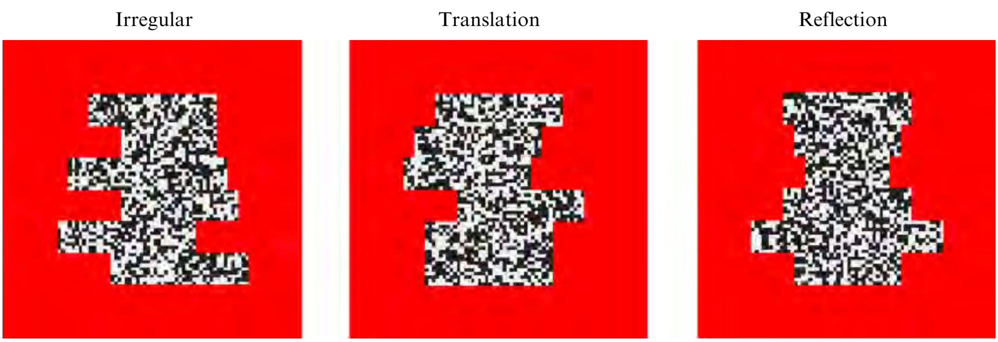

Figure 7. [In colour online] Examples of the stimuli of experiment 4. New stimuli were generated on each trial. The solid colour is used for illustration purposes, in the experiment the stimuli were random-dot stereograms. The object and the hole regions were identical and are therefore not shown separately, the only difference was depth order.

5.1 *Method*

5.1.1 *Participants.* Twelve students at the University of Liverpool participated. Their vision was normal or corrected to normal. Before the experiment started their stereovision was tested with the TNO stereo test.

5.1.2 *Stimuli and design.* The factors were transformation (reflection and translation), and type of object (object or hole). The hardware and the procedure were the same as in experiment 1. The total width of the square stimulus was 4.5 cm. The object and the hole regions were 3 cm in height and identical to each other in all respects except the depth order, as shown in figure 7 (these regions were also identical to the object and hole regions in experiment 2, see figure 3).

Each participant saw two balanced blocks of trials, one for reflection and one for translation. For half of the participants reflection was in the first block and for the other half it was in the second block. The total number of trials was 288 per observer.

5.2 *Results and discussion*

The factors analysed were the type of regularity and the type of stimulus. A repeated-measures ANOVA on logarithmically transformed RT confirmed that responses were faster for reflection than for translation ($F_{1,11} = 19.31$, $p < 0.01$), and for objects than for holes ($F_{1,11} = 43.23$, $p < 0.01$). There was also an interaction between the two ($F_{1,11} = 9.18$, $p = 0.01$). The average error rate was 14%. Two pre-planned t-tests were performed comparing objects and holes separately for reflection and for translation. As can be seen in figure 8, responses were faster to objects than to holes in the case of reflection ($t_{11} = 4.93$, $p < 0.01$), but not in the case of translation ($t_{11} = 0.09$, ns).

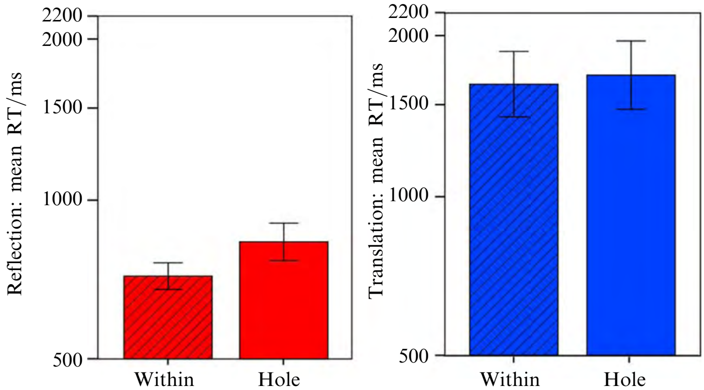

Figure 8. [In colour online] Results from experiment 4. The error bars show the standard error of the mean.

6 Conclusions

When human observers compare two contours and try to detect a match between the two, they find it easier to detect a reflection than a translation, as first noted by Mach (1885/1914). However, if the contours belong to different objects or surfaces, the type of surface is also important. As discussed in the introduction, there is an interaction between type of regularity and type of object: responses are faster for reflection when this is a property of a single object but they are faster for translation when this is a property of two objects. In experiment 1 I have tested this interaction using stereograms to ensure unambiguous surface interpretation. I have used a brief presentation time and computed indices of sensitivity (d') and bias (c'). Predictably the results show that sensitivity is higher for reflection than for translation. In addition, sensitivity is greater for reflection when a single surface is present, but it is greater for translation when two surfaces are present. The result for translation is remarkable in light of the fact that a between-surfaces advantage is contrary to either an object-based or a space-based prediction, because the between surfaces stimuli were larger (figure 1).

This result is consistent with the idea that translation is associated with a repetition, and therefore the presence of multiple objects (Treder and van der Helm 2007; Koning and Wagemans 2009). Note, however, that the pair of surfaces used in the stimuli of experiment 1 are not identical. The identity is only present at the level of contours, which makes the ecological argument less strong. That is, in most cases a repetition due to the presence of multiple copies of similar objects implies that the objects themselves are repeated. A translation of a pair of contours, on the other hand, is likely to originate from a once unitary object, which has subsequently split. This event is probably less frequent than the presence of multiple instances of the same object.

In experiment 2 stimuli were modified by means of an additional horizontal region joining the two surfaces present in the between-conditions of experiment 1 (see figure 3). Note that these regions carry no information relevant to the selection of the correct response. That is, nothing has changed with respect to the correspondence between contours that observers must detect. Nevertheless, the results do not show just a change in overall level of performance, but rather a change in the pattern of the interaction between type of object and type of transformation (compare figure 2 and figure 4). Specifically, in experiment 2 there was an object advantage for reflection but no difference between object and hole for translation. To further investigate this result experiment 3 introduced stimuli in which the foreground area was the same, on average, for all conditions. That is, the amount of disparity-carrying dots was the same in all conditions as was the ratio of foreground area over background area. The pattern of results for experiment 3 did not differ from the pattern for experiment 2.

Experiment 4 is a comparison between objects and holes in which only disparity specifies the difference between the conditions (same contours and same square envelope). There was an advantage for objects over holes for reflection but not for translation. This pattern, therefore, did not differ from the pattern of experiments 2 and 3. Although experiments 3 and 4 tried to control for the greater size of the holes stimuli, it is impossible to avoid the fact that for holes the contours belong to surfaces on the outside, as opposed to the inside in the case of an object. If attention spreads on surfaces, then border ownership will always give holes a handicap because attention has to spread farther away from the centre of the region of interest. If so, the lack of difference in performance for translation may be an actual advantage for holes over objects, masked by a spatial-attention disadvantage. This advantage would be in agreement with the idea that translation is consistent with multiple objects. However, as noted above, translated contours on separate objects are not the same as multiple objects. A related, but convoluted, hypothesis is as follows. Reflection is consistent with a single object, and reflection is coded by matching convexities (and concavities) around an axis (Hulleman and Olivers 2007). A by-product of efficient detection of reflection may be a difficulty in responding to its opposite. A translation within an object is the opposite of a reflection in the sense that, instead of matching convexities and concavities, we have a complete mismatch between convexities and concavities.

In the introduction I have discussed the literature on the interaction between type of regularity and type of object (eg Corballis and Roldan 1974). The type of object can be described as the context in which the regularity is embedded. This context can facilitate detection of regularity in some cases (a reflection within a surface but also a translation for contours of two surfaces). This interaction was confirmed by using a measure of sensitivity (d') but not using a measure of bias (c').

Experiments 2, 3, and 4 tested performance when detecting a correspondence across a hole (ground) region or a surface region. One hypothesis is that closure is the critical factor and therefore holes should behave like objects. This is in agreement with the idea, put forward by Palmer, that holes are treated as objects with respect to shape analysis (Palmer 1999; Palmer et al 2008; but see Bertamini 2006). The opposite possibility is that holes should behave as other ground regions, because the critical factor is whether the comparison is across a surface joining the pair of contours or across a gap. Note that this also would imply that number of objects is not a critical factor. For example, in experiment 2 there was always only one object present (either a simple object or an object-with-hole). Results do not agree entirely with either of these two possibilities. For reflection the critical factor seems to be whether the comparison is across a surface: there was an advantage for the within-object condition when compared to the between-objects and also to the hole conditions. Perhaps it is important that the axis of symmetry passes through a figural rather than a ground region. Note that the comparison between experiments 1 and 2 is a comparison between stimuli with identical degree of regularity (the pair of contours) but different number of objects. Number of objects does not appear a critical variable for detection of reflection.

The results for translation are more in agreement with a critical role for number of objects, in the direction of better performance when more objects are present. There was an advantage in detection of translated contours only when these belonged to two separate objects (experiment 1), but never when objects were compared to holes (experiments 2–4). This is consistent with the lock-and-key metaphor but also with the more recent proposal that translation is more often a signal of the presence of multiple objects (Koning and Wagemans 2009).

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