Regularity detection by haptics and vision

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ABSTRACT

For vision, mirror-reflectional symmetry is usually easier to detect when it occurs within one object than when it occurs across two objects. The opposite pattern has been found for a different regularity, repetition. We investigated whether these results generalise to our sense of active touch (haptics). This was done to examine whether the interaction observed in vision results from intrinsic properties of the environment, or whether it is a consequence of how that environment is perceived and explored. In four regularity detection experiments we haptically presented novel, planar shapes and then visually presented images of the same shapes. In addition to modality (haptics, vision), we varied regularity-type (symmetry, repetition), objectness (one, two) and alignment of the axis of regularity with respect to the body midline (aligned, across). For both modalities, performance was better overall for symmetry than repetition. For vision, we replicated the previously reported regularity-type by objectness interaction for both stereoscopic and pictorial presentation, and for slanted and frontoparallel views. In contrast, for haptics, there was a one-object advantage for repetition as well as for symmetry when stimuli were explored with one hand, and no effect of objectness was found for two-handed exploration. These results suggest that regularity is perceived differently in vision and in haptics, such that regularity detection does not just reflect modality-invariant, physical properties of our environment.

INTRODUCTION

The world that we experience is full of regularities. Most of the important objects that surround us, both living (plants, animals), and inanimate (such as tools, buildings, planets), are more or less mirror-symmetrical (Treder, 2010) and urban scenes are often designed with many repetitive and mirror-symmetrical patterns (Wu, Frahm & Pollefeys, 2010). It is not a mystery, then, why such regularities have always fascinated us, inspiring art and science.

It is important to begin by defining our terms since the terminology used to describe regularities can be confusing. In everyday language, symmetry is usually understood to refer only to bilateral, mirror-reflectional symmetry. However, in the scientific literature, symmetry is often taken to also encompass other regularities such as the repetition of a structure by a translation (translational symmetry) and the rotation of a structure about a fixed point (rotational symmetry). Symmetries in this wider sense have also been referred to as regularities or spatial transformations or Euclidean isometries. Here, we will discuss only two types of regularity: bilateral mirror-reflectional symmetry, which we will refer to as *symmetry*, and translational symmetry, which we will term *repetition*. We will use *regularity* to include both symmetry and repetition and *irregular* to refer to random stimuli. In our experiments we asked people to detect regularities when they occurred across pairs of *critical contours* which were either two opposite sides of one-object stimuli or two facing sides of two-objects stimuli.

Symmetry is known to be important for visual perception. We are extremely sensitive to it and can detect it rapidly (for reviews see Leeuwenberg, 2010; Treder, 2010; Tyler, 1995; van der Helm, 2014; Wagemans, 1997). Symmetry provides a powerful grouping principle for the segmentation and spatial representation of visual shapes and scenes (e.g., Chen & Sio, 2015; Locher & Nodine, 1973; Mach, 1886/1959; Palmer, 1989; Royer, 1981; Van der Helm & Leeuwenberg, 1996), for figure-ground segregation (Baylis & Driver, 2001; Driver, Baylis, & Rafal, 1992; Leeuwenberg & Buffart, 1984; Machilsen, Pauwels, & Wagemans, 2009), amodal completion (Kanizsa, 1985; van Lier, van der Helm & Leeuwenberg, 1995) and object recognition (Pashler, 1990; Vetter & Poggio, 1994), with symmetry helping to constrain the interpretation of 3D shapes (Pizlo, Li, Sawada & Steinman, 2014).

It has long been known that, for vision, symmetry is easier to detect than other regularities, such as repetition (Baylis & Driver, 1994, 1995; Mach, 1886/1959) or rotational symmetry (Julesz, 1971). This is one of several pieces of evidence that suggests that symmetry has greater goodness than repetition (Treder & van der Helm, 2007). In addition, Baylis and Driver (1994) found that increasing stimulus complexity (by increasing the number of discontinuities along the critical contours) had no effect on symmetry detection (provided that comparisons were made within a single object, see Baylis & Driver, 2001), but it made repetition detection harder. Baylis and Driver (1994, 2001) suggested that symmetrical information within an object may be processed in parallel, whereas repeated information must be processed serially. Baylis and Driver suggested that, in turn, this difference arose because symmetric objects have corresponding part decompositions (Hoffman & Richards, 1984). Specifically, they noted that the polarity of concavities and convexities along the axis of regularity are identical for objects with symmetrical sides, but are opposite for objects with repeated sides. If the visual system encodes part descriptions along critical contours in parallel, then symmetry detection could occur in parallel. In contrast, since objects with repeated contours have different part descriptions, then repetition may, instead, have to rely on detecting similarities along local contours. This may require effortful, serial processing of successive, short segments of contour. However, this account cannot explain the finding, described next, of an interaction between regularity-type and objectness in the visual detection of regularities, since the part decomposition for two-objects stimuli produces corresponding parts for symmetry, but not for repetition, just as it does for one-object stimuli (Koning & Wagemans, 2009; see also Figure 1).

Baylis and Driver (1995) and Bertamini, Friedenberg and Kubovy (1997; see also Friedenberg & Bertamini, 2000) used a regularity detection task with visual shapes similar to those depicted in Figure 1. In both studies, symmetry detection was better when the two critical contours being compared belonged to two sides of the same object rather than to facing sides of two separate objects. In contrast, repetition was generally better detected when the two critical contours belonged to two objects rather than just one. Baylis and Driver (1995) and Bertamini et al. (1997) explained the interaction between regularity-type and objectness as resulting from the use of different cognitive matching strategies to detect symmetry versus repetition. They suggested that the repeated, two-objects stimuli could be mentally translated towards each other to form a match, either like joining two pieces of a jigsaw puzzle (Baylis & Driver, 1995) or like putting a key in its lock (Bertamini et al. 1997).

Koning and Wagemans (2009) suggested an alternative way to explain this one-object advantage for symmetry detection and two-objects advantage for repetition detection. They proposed that this interaction of regularity-type by objectness might depend on differences in the visual encoding of spatial relations within and between objects, rather than on high-level, cognitive matching strategies. Koning and Wagemans (2009; see also Treder & van der Helm, 2007; van der Helm & Treder, 2009) argued that, for visual perception, symmetry and repetition are both important cues which help us to decide how to segment a scene into objects.

Specifically, symmetry may be used as a cue to the location of a single object, so symmetry will be easier to detect for one-object stimuli, whereas repetition may be used as a signal to the presence of similarly shaped objects, so it may be easier to detect for two-objects stimuli (see Figure 2).

Koning and Wagemans (2009) tested their account using stimuli like those used by Baylis and Driver (1995) and Bertamini et al. (1997) except that their stimuli appeared to be 3D, planar objects slanted in depth. This slanted view was used to try to reduce figure-ground ambiguity, which could have been an issue for earlier studies which presented 2D shapes like those shown in Figure 1. In addition, showing slanted views prevented the use of cognitive matching strategies involving 2D mental translations. Koning and Wagemans (2009) replicated the interaction of regularity-type by objectness previously found by Baylis and Driver (1995) and Bertamini et al. (1997). They therefore concluded that the interaction was caused by structural coding of the stimuli, rather than the choice of cognitive matching strategies[1].

One important way to further test whether the interaction of regularity-type by objectness depends on general properties of the perceptual processing of object structure, rather than on specific, cognitive matching strategies, or on properties of the external, physical environment, is to examine non-visual regularities. The research discussed so far investigated only the visual detection of regularities, but vision is not the only sensory modality that allows us to recognize objects in the world. Many objects can be efficiently recognized and detected by haptics, our sense of active touch (e.g., Cecchetto & Lawson, 2015; Lawson & Bracken, 2011). Given that regularities are known to be important for the visual perception of objects then regularities might also be expected to influence haptic perception. There has been relatively little research investigating haptic perception of regularities. A few studies have investigated haptic symmetry detection (for a recent review, see Cattaneo, Bona, Bauer, Silvanto, Herbert, Vecchi & Merabet, 2014) but, as far as we are aware, no other researchers have investigated repetition detection in haptics.

Vision and haptics are exposed to much the same environment and they interact with many of the same objects. They are both expert at perceiving many of the same spatial features, like object shape, size and orientation. They also share many processing goals, including that of recognizing objects (e.g., Craddock & Lawson, 2008, 2009; Lawson 2009; Martinovic, Lawson & Craddock, 2012). Furthermore, object naming using haptics alone is surprisingly fast and accurate (~2s and <10% errors, Lawson & Bracken, 2011). Haptics in the absence of vision is known to be sensitive to symmetry in both blind and normally sighted participants, and for both explicit, perceptual matching and for implicit, short-term memory tasks (e.g., Ballesteros, Manga & Reales, 1997; Ballesteros, Millar & Reales, 1998; Ballesteros & Reales, 2004; Cattaneo, Fantino, Silvanto, Tinti, Pascual-Leone & Vecchi, 2010; Cattaneo, Vecchi, Fantino, Herbert & Merabet, 2013; Locher & Simmons, 1978; Millar, 1978).

In summary, for vision, Koning and Wagemans (2009; see also Baylis & Driver, 1995; Bertamini, 2010; Bertamini et al., 1997; Friedenberg & Bertamini, 2000) reported that symmetrical pairs of contours were detected more easily when they belonged to the same object, rather than to two separate objects, but that the opposite pattern occurred for repetition. This interaction may occur because the visual system uses symmetry to signal the presence of a single object and repetition to indicate the presence of multiple objects (e.g., Koning & Wagemans, 2009; Treder & van der Helm, 2007; van der Helm & Treder, 2009). If this is the case then, importantly, we may be able to use effects on regularity detection to examine the nature of objectness itself, and to investigate whether this differs for vision and for touch. Despite the central role that objects play in cognitive science it has proven difficult to formally define what constitutes a visual object (Feldman, 2003), whilst in haptics this topic does not appear to have been addressed at all (Lawson, Ajvani & Cecchetto, in press). Researchers claiming to manipulate objectness often make little attempt to justify their choice of stimuli. Here, in order to try to understand the nature of objectness, and whether this differs across modalities, we directly compared the detection of symmetry and repetition across vision and touch for objects specified by solid surfaces.

We report the results of four experiments in which we compared regularity detection by haptics (Experiments 1 and 3) and by vision (Experiments 2 and 4) for the same set of 3D planar shapes. The task was always to distinguish regular (symmetrical or repeated) stimuli from irregular (random) stimuli. One group of participants was tested in Experiments 1 and 2 and another group in Experiments 3 and 4, with all participants doing the haptic task followed by the visual task. We tested whether the interaction of regularity-type by objectness that has been reported for vision would also occur for haptics. If regularities and the nature of objects are defined solely by properties of our external environment, then how information about them is acquired should not influence regularity detection, regardless of the modality of presentation. In contrast, if the way in which vision extracts and uses information affects regularity detection then effects on regularity detection may be very different for haptics, since the time-course and manner of haptic exploration differs substantially from that of vision.

Experiment 1

Participants used their hands to freely explore novel, planar 3D shapes, see Figure 3.

We had three aims. First, we investigated whether, for haptics, participants found it easier to detect symmetry compared to repetition, as has been reported for vision. Second, we investigated whether the interaction of regularity-type by objectness found for vision would also occur for haptics. If so, then symmetry should be easier to detect for one-object than two-objects stimuli and vice versa for repetition. Third, as discussed below, we tested whether any symmetry advantage was greater if the axis of regularity was aligned to the participant's own body midline, aiding the use of a salient, body-based reference frame to encode symmetry.

We manipulated the alignment of the axis of regularity because this is known to exert a powerful influence on visual regularity detection. Vertical symmetry (when the axis of regularity is aligned with the body midline) is usually easier to detect than both horizontal symmetry (when the axis of regularity runs across the body midline) and oblique symmetry (Herbert & Humphrey, 1996; Locher & Wagemans, 1993; Mach, 1886/1959; Rossi-Arnaud, Pieroni, Spataro, & Baddeley, 2012; Wagemans, Van Gool & d'Ydewalle, 1992; Wenderoth, 1994). Fewer studies have compared the visual detection of repetition at different axis alignments. Corballis and Roldan (1975) and Corballis, Zbrodoff and Roldan (1976) presented both symmetrical and repeated stimuli at different orientations and found an advantage for aligned stimuli but they asked participants to discriminate between the two types of regularity (and not, as is usual, between regular and irregular stimuli). Baylis and Driver (1994) found an advantage for detecting symmetry if the stimuli were aligned with, rather than running across, the body midline, but no such effect for the detection of repetition. Farell (2015) replicated this result of an alignment advantage for detecting symmetry, but not repetition, for stimuli slanted in depth, as well as for stimuli presented in the usual frontoparallel plane. In contrast, Friedenberg and Bertamini (2000) found weak alignment effects with a general trend for an alignment advantage for repetition detection as well as symmetry detection.

Few studies have investigated the effects of axis alignment on haptic regularity detection. Cattaneo et al. (2010, 2013) found an advantage for remembering frontally presented symmetrical relative to asymmetrical stimuli for sighted participants if the axis of symmetry was aligned with, rather than running across the body midline. This result was recently extended to explicit regularity detection by Lawson et al (in press). We found that haptic symmetry detection was easier for aligned compared to across stimuli, whereas haptic repetition detection showed no consistent effects of axis alignment[2].

The body midline can provide a reliable axis for egocentrically coding the position of objects in the environment and of body parts (the head, limbs, hands and fingers) as well as the direction of actions. For stimuli aligned with the body midline, symmetry detection may be privileged because the axis of symmetry of the stimuli is then coincident with a salient reference frame based on the axis of symmetry of the participant's own body, relative to stimuli aligned across the body midline (Ballesteros et al, 1997; Ballesteros & Reales, 2004). Thus, for both modalities, we expected to find an alignment advantage for detecting symmetry, but not for repetition. Any such effects, due to body-centric coding of symmetrical spatial relations, would indicate that regularity detection does not merely reflect properties of our external, physical environment but, instead, is influenced by how we perceptually acquire and process information. For vision, the prediction that axis alignment should aid the detection of symmetry, but not of repetition, is supported by the results of Baylis and Driver (1994) and Farell (2015), but not by those of Friedenberg and Bertamini (2000), so the evidence to date is mixed, whilst for haptics this issue has only been tested once, by Lawson et al (in press), and here the results supported the prediction.

Method

Participants There were 32 participants (26 females, mean age = 23 years, range 18-46). They were either volunteers or undergraduate students from the University of Liverpool who participated for course credit. All the participants self-declared as right-handed with no known conditions affecting their sense of touch. All the experiments reported here received approval from the local ethics committee.

Materials Participants sat in a normally lit lab behind a 70cm high table. A thick curtain hung in front of the table, blocking their view of the stimulus and their hands. Participants centred their body midline with the centre of the frame where stimuli were presented. The nearest side of the stimulus was 25cm from the edge of the table and approximately 40cm from the participant's body.

A set of eight stimuli (regular/irregular x symmetrical/repeated x one-object/two-objects) were created from each of 40 unique lines to produce a set of 320 stimuli. Each unique line was placed on the left of a 10cm high vertical axis of regularity to create the left critical contour. The top and bottom of each unique line was 5cm horizontally left of the top and bottom respectively of this vertical axis. Each unique line had five segments which were produced by varying the position of four vertices. Each vertex was between 1cm and 9cm horizontally to the left of the axis of regularity and was at least 1cm vertically below the top of the unique line and 1cm vertically above the bottom of it, and was separated by between 1cm and 4cm vertically and horizontally from the next, nearest vertex. The left critical contour was identical for the eight stimuli created from a given unique line. The second critical contour for each stimulus was created on the right side of the vertical axis. The right contour was the symmetrical or the repeated version of the left contour for regular stimuli and it was the symmetrical or repeated version of a different unique line for irregular stimuli. For the irregular stimuli, each of the 40 unique lines was paired with another one. For example, irregular stimuli with line 15 as the left critical contour always had line 30 as the right critical contour, whilst irregular stimuli with line 30 on the left always had line 4 on the right, see Figure 4.

The stimuli were cut from 10cm x 10cm squares of black, 0.5cm thick foam-board. Each stimulus was glued onto a 10cm x 10cm brown cardboard base. Stimuli were presented by slotting them into a fixed blue frame with a 10.1cm x 10.1cm aperture (see Figure 3). This prevented stimuli from moving during haptic exploration. Two 0.5cm wide, 10cm high vertical bars flanked the left and right sides of the aperture in the frame. These bars were adjacent to the straight left and right sides of the left and right objects respectively for two-objects stimuli. The bars provided a frame for the one-object stimuli which served to equate the overall width of the one-object and two-objects stimuli, replicating the stimulus design used by Koning and Wagemans (2009). Two white patches on the bottom corners of the frame marked the resting positions for each hand. Each stimulus could be presented with the axis of regularity either aligned with the body midline, or rotated 90^0 to the left so that it ran across the body midline.

Design The 320 stimuli were divided into four equal subsets. Each participant was presented with only one subset. Within this subset, each of the 40 unique lines appeared as the left critical contour once in a symmetrical stimulus and once in a repeated stimulus. The symmetrical stimuli and repeated stimuli were presented in two separate blocks of 40 trials each. Within each block, half the stimuli were regular and half were irregular, with ten of each type being one-object stimuli, and ten being two-objects stimuli. Trials within a block were presented in a fixed, pseudo-random order. Half the participants felt aligned stimuli, and half felt across stimuli, with eight participants from each group doing the symmetry detection block first, and the remaining eight participants doing the repetition block first. Two participants from each of these four subgroups were assigned to each of the four stimulus subsets.

Procedure Participants were visually shown four practise stimuli (a regular and irregular example of a one-object and a two-objects stimulus) of the regularity-type that they were about to feel, with the appropriate alignment of the axis of regularity. They were instructed about the regularity-type (symmetry or repetition) that they had to detect. They then did four practise trials when they felt each of the practise stimuli in turn, followed by the first experimental block of 40 trials. The participants were then told about the new type of regularity that they would have to detect, and they were shown four new practise stimuli. They then did four practise trials before doing the second experimental block of 40 trials. Finally, participants were asked whether they had seen any of the stimuli. The experiment took around one hour.

At the start of each trial, the experimenter placed a stimulus in the frame whilst the participant put their hands on the two patches on the frame that marked the resting positions for each hand. The experimenter then triggered an auditory ‘go now’ signal from the computer. This signal indicated that the participant could move their hands from the resting positions to touch the stimulus. They responded by saying "same" to regular stimuli and "not" to irregular stimuli as quickly and accurately as possible. Participants were not told how to feel the stimuli and they were allowed to freely explore them using one or two hands. Reaction time was measured from the offset of this signal to the onset of the participants' vocal response using a microphone hung 10cm in front of their head. The experimenter recorded their answer using the keyboard. This triggered a high or a low pitch feedback sound which indicated whether the response was correct or wrong respectively.

Results and Discussion

In Experiment 1, two participants did not fully understand the task and were replaced. In all of the experiments reported in this paper, analyses of variance (ANOVAs) were conducted on the mean correct reaction times (RT) and percentage of errors for regular trials only, and on sensitivity (d') for all trials. In Experiments 1 and 3, correct haptic RT faster than 3s or slower than 35s were removed as outliers, and in Experiments 2 and 4, correct visual RT faster than 0.4s and slower than 3.5s were removed as outliers (0.7%, 0.4%, 1.1% and 0.2% of trials for Experiments 1, 2, 3 and 4 respectively). Appendix 1 presents the full ANOVAs for RT, errors and sensitivity (d') for Experiment 1. Here, we focus on the two most important interactions, and we report results for RT and errors for regular trials only, for consistency with the analyses of Koning and Wagemans (2009), and since it is difficult to theoretically interpret the results for irregular trials.

First, the interaction of regularity-type x objectness was not significant for either RT [$F(1,30) = 0.35$, $p = .86$, partial $\eta^2 = .001$], or errors [$F(1,30) = 0.06$, $p = .82$, partial $\eta^2 = .00$]. In particular, the two-objects advantage that has been reported for visual repetition detection (e.g., Koning & Wagemans, 2009) was not found here for haptic repetition detection.

Second, the interaction of regularity-type x alignment was not significant for RT [F(1,30) = 2.18, p = .15, partial η^2 = .07], but it was significant for errors [F(1,30) = 18.32, p < .001, partial η^2 = .38]. Symmetry was detected significantly more accurately (p < .05) for aligned (8.9s, 3%) than for across (10.9s, 21%) trials in a post-hoc Newman-Keuls analysis. In contrast, accuracy to detect repetition was not significantly different for aligned (12.1s, 33%) and across (12.8s, 30%) trials. This difference meant that the advantage for symmetry over repetition was much greater for aligned trials (30%) than for across trials (9%), with the same trend for RT. Thus, as we had predicted, symmetry detection benefitted more than repetition detection from aligning the axis of regularity with a salient reference frame centred on the participant's body midline. This result replicates the regularity-type x alignment interaction that we reported in Lawson et al. (in press) for detecting regularity across critical lines only (rather than across critical contours of planar shapes, as we used here).

Next, for ease of comparison with subsequent studies, and to simplify presentation of the results, we present below separate analyses for the aligned and across groups:

For the aligned group, regularity-type was significant for both RT [F(1,15) = 19.56, p < .001, partial η^2 = .57], and errors [F(1,15) = 60.14, p < .001, partial η^2 = .80]. Detection was easier for symmetry (8.9s, 3%) than repetition (12.1s, 33%). Objectness was not significant for RT [F(1,15) = 3.57, p = .08, partial η^2 = .19], or for errors [F(1,15) = 0.81, p = .38, partial η^2 = .05]. Detection of one-object stimuli (10.1s, 19%) was similar to that of two-objects stimuli (10.9s, 17%). Finally, the interaction of regularity-type x objectness was not significant for RT [F(1,15) = 0.06, p = .81, partial η^2 = .00], or for errors [F(1,15) = 0.00, p = .99, partial η^2 = .00], see Figure 5.

For the across group, regularity-type was significant for both RT [F(1,15) = 9.43, p = .008, partial η^2 = .39], and errors [F(1,15) = 10.05, p = .006, partial η^2 = .40]. Again, detection was easier for symmetry (10.9s, 21%) than repetition (12.8s, 30%). In addition, objectness was significant for both RT [F(1,15) = 27.71, p < .001, partial η^2 = .65], and errors [F(1,15) = 19.91, p < .001, partial η^2 = .57]. In contrast to aligned stimuli, one-object stimuli (10.3s, 13%) were easier to detect than two-objects stimuli (13.3s, 38%). Finally, the interaction of regularity-type x objectness was not significant for RT [F(1,15) = 0.20, p = .66, partial η^2 = .02], or for errors [F(1,15) = 0.10, p = .76, partial η^2 = .01], see Figure 5.

In Experiment 1 we found an advantage for haptically detecting symmetry compared to repetition, similar to the general symmetry advantage found in vision. However, unlike vision, no interaction was found between regularity-type and objectness, either for across or for aligned stimuli. In particular, we did not find the two-objects advantage for repetition that has been reported for vision (Koning & Wagemans, 2009). In Experiment 1 there were significant main effects and interactions involving the factors of both objectness and of regularity-type. Thus the lack of interaction between these two factors was not because these factors were unimportant to haptics, or because objectness was not perceived haptically.

Overall, we found some similarities between haptic regularity detection in Experiment 1 and previous findings for visual regularity detection. Specifically, there was an overall symmetry advantage and an axis alignment advantage for symmetry detection (e.g., see Baylis & Driver, 1994; Lawson et al., in press). Importantly, though, the lack of a regularity-type by objectness interaction suggests that vision and haptics may perceive regularities in different ways, with the nature of objectness differing across vision and touch. However, as discussed by Koning and Wagemans (2009), the regularity-type by objectness interaction has not always been obtained for visual regularity detection. Therefore before drawing any strong conclusions based on these findings, we needed to confirm that the task and stimuli that we used to test haptic regularity detection in Experiment 1 would elicit the expected interaction for vision. This was done in Experiment 2

Experiment 2

Experiment 2 largely replicated Experiment 1 except that the stimuli were presented visually, on a vertical monitor, as either pictorial or stereoscopic images, rather than haptically, as 3D planar shapes placed on a horizontal surface. For the pictorial images, the same photo was shown to both eyes. For the stereoscopic images, two different photos, taken from locations separated horizontally by 6cm, were shown to the left and to the right eyes. As in Experiment 1 we manipulated regularity-type (symmetry or repetition), objectness (one or two-objects) and alignment (axis of regularity aligned with or running across the participant's body midline). Since visual regularity detection was expected to be much easier than haptic regularity detection, participants did four times more trials. Photos of the stimuli used in Experiment 1 were taken from a slanted views so that they appeared as 3D planar objects (see Figure 6). In their visual symmetry detection studies Koning and Wagemans (2009; see also van der Vloed, Csathó & van der Helm, 2005) also used slanted views of planar stimuli to try to make figure-ground assignment easier, and to limit the use of image-based, mental translation strategies.

Based on previous visual research (Mach, 1886/1959), we expected symmetry to be easier to detect overall compared to repetition. Second, unlike for haptic regularity detection, for visual regularity detection we expected an interaction between regularity-type and objectness. Specifically, we predicted symmetry detection to be easier for one-object compared to two-objects stimuli, and the reverse pattern to occur for repetition detection (Koning & Wagemans, 2009). Third, as explained above, we expected better symmetry detection for aligned compared to across stimuli, whereas we expected little or no alignment advantage for repetition detection (Baylis & Driver, 1994; Farell, 2015; Lawson et al., in press). Finally, we presented stimuli both pictorially and stereoscopically to test whether any effects of objectness were greater for stereoscopic stimuli, where figure-ground ambiguity should be reduced relative to pictorial stimuli.

Method

Participants The same 32 participants who took part in Experiment 1 subsequently did Experiment 2 after a delay of 2-10 days. They all had normal, or corrected to normal, vision and stereovision, which was assessed using the Stereo Fly Test (Stereo Optical Company, Inc.).

Materials The stimuli were based on photos of the 3D planar shapes used in Experiment 1. Photos were taken using an 8-megapixel camera mounted on a tripod and with constant lighting. The position of the camera from the stimuli was similar to the participant's head position in Experiment 1, about 40cm away from the stimulus at an angle of around 45°. A sliding base was used to take photos from three fixed positions (3cm left, central and 3cm right, see Figure 6). Six photos were taken of each of the 320 stimuli (3 positions x 2 alignments). A black mask was then digitally superimposed around each photo (see Figure 7) so that only the stimulus and the blue frame around it were visible. The stimuli were presented on a Sony monitor with a resolution of 1280 x 1024 pixels and a refresh rate of 120 Hz using Psychopy software (Peirce, 2009). The top of the monitor was at approximately the same height as the top of the participant's head. Participants sat around 60cm away from the monitor and they were instructed to centre their body midline to the centre of the monitor. Images were presented using a NuVision infrared emitter and NuVision stereoscopic shutter glasses. The left and right images were interleaved so the effective vertical resolution and refresh rate were halved to be 1280 x 512 pixels at 60 Hz. The left and right images were shown to the left and right eyes respectively in the stereoscopic condition, whilst the central image was shown to both the left and right eyes in the pictorial condition.

Design Participants did the same block order (symmetry then repetition or vice versa) as they had done in Experiment 1. However, each block included all possible 160 trials rather than only the subset of 40 of these trials that they did in Experiment 1. Each block was split into two halves, with the first half using the same alignment that the participant had had in Experiment 1, and the second half having the other alignment. This meant that for a given participant the first 40 haptic trials in Experiment 1 (for example, symmetry with an aligned axis for participant 1) were identical to the initial 40 visual trials in Experiment 2 for that participant, and the remaining 40 trials in Experiment 1 (repetition with an aligned axis for participant 1) were identical to the first 40 visual trials of the second block of Experiment 2 for that participant. Within each block of 80 trials, half of the participants did 40 stereoscopic trials followed by 40 pictorial trials and the remaining participants did these trials in the reverse order.

Procedure The experimenter explained the task and showed the same practice stimuli as in Experiment 1. Participants were not told about the occurrence of stereoscopic versus pictorial stimuli. Before starting each subset of 80 trials, participants were told the type of regularity they were going to detect (symmetry or repetition) and the alignment of the axis of regularity (aligned or across their body midline). They then did 10 practice trials comprising five regular and five irregular trials, and also five stereoscopic and five pictorial trials.

Each trial started by presenting a white fixation cross on a black background for 1s. This was replaced by the stimulus which remained on the screen until the participant responded or for 4s. They were told to respond as quickly and accurately as possible, using the keyboard, by pressing ‘s’ for regular stimuli and ‘k’ for irregular stimuli. A feedback sound indicated whether their response was correct. Failure to respond within 4s triggered the error feedback sound, and the trial was recorded as an error. The experiment took around 40 minutes.

Results and Discussion

Appendix 2 presents the full ANOVAs for RT, errors and sensitivity (d') for Experiment 2. In these analyses the main effect of visual presentation was not significant, and nor were any interactions with this factor and so, below, as in Experiment 1, we focus on the two most important interactions. All pairwise differences noted below were significant ($p < .05$) in post-hoc Newman-Keuls analyses.

First, the interaction of regularity-type x objectness was significant for both RT

[$F(1,31) = 162.02$, $p < .001$, partial $\eta^2 = .84$], and errors [$F(1,31) = 84.19$, $p < .001$, partial $\eta^2 =.73$]. Detecting symmetry was significantly faster, though not more accurate, for one-object (.89s, 3%) compared to two-objects (.95s, 4%) stimuli. In contrast, repetition was both slower and less accurately detected for one-object (1.49s, 17%) compared to two-objects (1.26s, 5%) stimuli.

Second, the interaction of regularity-type x alignment was significant for both RT [$F(1,31) = 66.82$, $p < .001$, partial $\eta^2 = .68$], and errors [$F(1,31) = 25.27$, $p < .001$, partial $\eta^2 = .45$]. For symmetry, there was no significant difference between the detection of aligned (.89s, 3%) and across (.95s, 4%) stimuli, though the trend was for aligned stimuli to be easier. In contrast, for repetition it was harder to detect aligned (1.56s, 15%) compared to across (1.19s, 7%) stimuli. Although there was a greater alignment advantage for symmetry detection than for repetition detection, this interaction was not quite as predicted. However, issues with the use of slanted views in Experiment 2 meant that we revisited this issue in Experiment 4, and so we return to further discuss this interaction there.

Next, to simplify presentation of the results, and to aid comparison with other experiments, we present below separate analyses for aligned stimuli, and for across stimuli.

For aligned stimuli, regularity-type was significant for both RT [$F(1,31) = 118.66$, $p < .001$, partial $\eta^2 = .79$], and errors [$F(1,31) = 73.26$, $p < .001$, partial $\eta^2 = .70$]. Detection was easier for symmetry (0.89s, 3%) than for repetition (1.56s, 15%). Objectness was significant for both RT [$F(1,31) = 24.86$, $p < .001$, partial $\eta^2 = .45$], and errors [$F(1,31) = 43.66$, $p < .001$, partial $\eta^2 = .59$]. Detection was harder for one-object stimuli (1.26s, 13%) than two-objects stimuli (1.18s, 5%). Finally the interaction of regularity-type x objectness was significant for both RT [$F(1,31) = 143.87$, $p < .001$, partial $\eta^2 = .82$], and errors [$F(1,31) = 75.54$, $p < .001$, partial $\eta^2 = .71$], see Figure 8. Symmetry detection was faster, but not significantly more accurate, for one-object (0.83s, 2%) compared to two-objects (0.94s, 4%) stimuli. In contrast, repetition detection was both slower and less accurate for one-object (1.70s, 23%) than for two-objects (1.41s, 6%) stimuli.

For across stimuli, regularity-type was significant for both RT [$F(1,31) = 26.56$, $p < .001$, partial $\eta^2 = .46$], and errors [$F(1,31) = 4.39$, $p = .044$, partial $\eta^2 = .12$]. Detection was, again, easier for symmetry (0.95s, 4%) than repetition (1.19s, 7%). Objectness was significant for both RT [$F(1,31) = 24.66$, $p < .001$, partial $\eta^2 = .44$], and errors [$F(1,31) = 4.79$, $p = .036$, partial $\eta^2 = .13$]. Detection was again harder for one-object stimuli (1.11s, 7%) than two-objects stimuli (1.03s, 5%). Finally, the interaction of regularity-type x objectness was significant for both RT [$F(1,31) = 44.19$, $p < .001$, partial $\eta^2 = .59$], and errors [$F(1,31) = 20.62$, $p < .001$, partial $\eta^2 = .39$], see Figure 8. There was no significant difference in symmetry detection between one-object (0.95s, 4%) and two-objects (0.96s, 5%) stimuli. In contrast, repetition detection was both slower and less accurate for one-object (1.27s, 10%) compared to two-objects (1.1s, 4%) stimuli.

Consistent with previous research in vision, in Experiment 2 we obtained both an overall advantage for symmetry detection relative to repetition detection, and an interaction between regularity-type and objectness. The exact nature of this interaction has varied across previous studies. We found a one-object advantage for symmetry detection (significant for aligned but not for across stimuli) and a powerful two-objects advantage for repetition detection for both stimulus orientations. Koning and Wagemans (2009) also found a one-object advantage for symmetry detection and a two-objects advantage for repetition detection when they tested stimuli which appeared as slanted, 3D planar shapes. However, this interaction was not significant when they tested 2D versions of their stimuli (see their General Discussion) and, as Koning and Wagemans (2009) discuss, other studies have either not directly tested for the interaction, or have not always found both comparisons to be significant.

Koning and Wagemans (2009) suggested that the strong regularity-type by objectness interaction that they reported may have arisen because figure-ground assignment was clear for the slanted views of 3D objects that they used. In contrast, most previous research has found weaker interactions and has used 2D, frontoparallel views of planar stimuli where figure-ground assignment may be more ambiguous (e.g., Baylis & Driver, 1995; Bertamini et al., 1997). Contrary to this proposal, in Experiment 2 the regularity-type by objectness interaction was no stronger when stimuli were presented stereoscopically (which should have reduced figure-ground ambiguity) rather than pictorially. However, our stimuli were raised by only 0.5cm above the base, so the extra stereoscopic depth cues may not have added much to the depth cues which were available pictorially. In Experiment 4 we presented frontoparallel views of planar stimuli to check whether we still obtained the same regularity-type by objectness interaction.

In Experiment 2, we found the same general pattern of results whether the axis of regularity of the stimuli was aligned with, or ran across, the body midline. However, the size of the one-object cost for repetition was larger for aligned than for across stimuli (see Figure 8 and Appendix 2). This enhanced cost resulted in an unexpected, overall advantage for across stimuli in Experiment 2. As outlined above, we had instead expected any effect of the alignment of the axis of regularity to produce an advantage for symmetrical stimuli aligned with the body midline. This prediction was supported by the results for haptic regularity detection in Experiment 1. In Experiment 4 we investigated whether the surprising across advantage for visual regularity detection that we observed in Experiment 2 was due to image-based distortions arising from the use of slanted rather than frontoparallel views.

Experiment 3

When we investigated haptic regularity detection in Experiment 1, we allowed our participants to freely explore the stimuli. From our informal observations, it seemed that stimulus alignment influenced the manner of exploration. We further speculated that the choice of exploration strategy might influence regularity detection because the manner of exploration could be used as a cue to objectness (Lawson et al., in press). When the axis of regularity ran across the body midline there appeared to be a diversity of exploration styles, with people using a mix of one-handed and two-handed exploration. In contrast, when the axis of regularity was aligned to the participants' body midline, exploration seemed to be consistently two-handed. This might simply be because this was a more comfortable way to explore aligned stimuli. However, two-handed exploration might also make the symmetry of aligned stimuli easier to detect because this regularity then matches the symmetry of the arm and hand positions and movements made during stimulus exploration (Ballesteros et al, 1997; Ballesteros & Reales, 2004). In order to check our informal observations we ran an observational study to record the exploration strategies used on a subset of the trials used in Experiment 1.

Free exploration observation study

We tested 24 right-handed participants in order to provide objective data about people's preferred exploration strategy for regularity detection when, as in Experiment 1, no instructions were given about how to feel the stimuli. Participants did 16 trials from Experiment 1 which came from a mix of four conditions varying regularity-type (symmetry or repetition) and objectness (one or two objects). Half the participants felt stimuli aligned with their body midline, and half felt across stimuli. On each trial, we recorded which fingers of which hands people used to explore the stimuli.

Confirming our informal observations from Experiment 1, we found a strong preference for two-handed exploration of aligned stimuli. Ten of the 12 participants who felt aligned stimuli used two hands on every trial, exploring each stimulus from top to bottom. Most used both of their index fingers, often assisted by their thumbs or middle fingers. One participant used two-handed exploration on all but one trial whilst the final participant used mainly two-handed (11/16 trials) exploration. There were only six one-handed trials in total (3% of all trials) and these all occurred for one-object stimuli. The domination of two-handed exploration for aligned stimuli may have contributed to the advantage for detecting symmetry compared to repetition for aligned stimuli in Experiment 1. If both hands touch equivalent points on a pair of symmetrical, aligned contours they remain equidistant from the body midline as they move up and down the contours. This could be used as a cue to the presence of symmetry. In contrast, for repetition if both hands touch equivalent points then they are usually at different distances from the axis of the body midline during exploration, so coding information relative to this axis would not provide any special benefit.

Exploratory styles were much more diverse for the 12 participants who felt across stimuli. This was, again, consistent with our informal observations in Experiment 1. All participants used a mix of one-handed and two-handed exploration. One-handed exploration usually involved having the index finger on the upper contour and the thumb on the lower contour, whilst two-handed exploration usually involved both index fingers, or both middle fingers. One-object stimuli were usually explored with one hand (82% trials) whereas two-objects stimuli were more likely to be explored with two hands (64% trials). Within these general preferences there was much diversity in individual's strategies. Three participants explored most stimuli with one-hand (14/16, 15/16 and 15/16 trials). One participant always explored one-object stimuli with one hand and two-objects stimuli with two hands. Six further participants showed half of this consistent pattern (two explored all one-object stimuli with one hand, whilst four explored all two-objects stimuli with two hands; all six used a mix of one-handed and two-handed exploration for the other type of stimuli). The remaining two participants used a mix of one-handed and two-handed exploration for both one-object and two-objects stimuli. Thus although objectness influenced how most people explored across stimuli there was considerable variation in the exploration strategies used.

This free exploration observation study revealed that two-handed exploration dominated for aligned stimuli. This suggests that people would have consistently used two hands to explore the aligned stimuli in Experiment 1. This, in turn, may have specifically benefitted symmetry detection in Experiment 1, since body position and movements during exploration would also be symmetrical about the participant's body midline (Ballesteros et al, 1997; Ballesteros & Reales, 2004). In contrast, for stimuli with the main axis of regularity running across the body midline, the free exploration observation study suggested that a more complex mix of exploration strategies would have been used in Experiment 1. In order to investigate whether choice of exploration strategy affects haptic regularity detection, we conducted a follow-up study to Experiment 1. In Experiment 3, participants were explicitly instructed to explore across stimuli by either using one hand (using the index finger and thumb of their dominant right hand) or two hands (using both index fingers). Experiment 3 thus replicated the across group condition used in Experiment 1, except that people were told how to explore the stimuli. We investigated whether specifying one-handed versus two-handed exploration influenced the detection of symmetry and repetition for one-object and two-objects stimuli, because exploration strategy may be used as a cue to objectness (Lawson et al., in press).

Method

Participants There were 32 participants (26 females, mean age = 21 years, range 17-31). They were either volunteers or undergraduate students from the University of Liverpool who participated for course credit. All the participants self-declared as right handed, with no known conditions affecting their sense of touch.

Materials The same set of 320 stimuli used in Experiment 1 was also used here. However, all the stimuli were presented with their axis of regularity running across the body midline.

Design The design was identical to Experiment 1 except that the between-subjects factor of axis alignment was replaced by a between-subjects factor of exploration (one-handed or two-handed). Sixteen participants were assigned to the one-handed group, and the remaining participants were assigned to the two-handed group. For both groups, the right index finger always felt the uppermost critical contour whilst the right thumb (for the one-handed group), or the left index finger (for the two-handed group), always touched the lower critical contour (see Figure 9).

Procedure The procedure was similar to Experiment 1 except that participants were told how to explore the stimuli, and the experimenter monitored them during the experiment to ensure that they complied with their instructions. Also, since all of the stimuli had the axis of regularity running across the participant's body midline, the two resting patches were placed on their left side, near to the left end of the two critical contours (see Figure 9). This aided finding the contours and it forced exploration to start in the same way for everyone. The experiment took around one hour.

Results and Discussion

Two participants in Experiment 3 were replaced because their performance was close to chance. There was one empty cell for RT which was filled by the mean for that condition. In order to compare across different exploration conditions, the analyses included the results for the across group in Experiment 1. This group did the same task with the same stimuli as the two groups in Experiment 3, but they were allowed to freely explore the stimuli. Appendix 3 presents the full ANOVAs for RT, errors and sensitivity (d') for Experiment 3. As in the previous experiments, we focus here on the most theoretically interesting effect, namely the regularity-type by objectness interaction. This was not significant for RT [F(1,45) = 3.46, p = .07, partial $\eta2$ = .07], or for errors [F(1,45) = .05, p = .2, partial $\eta2$ = .04]. To simplify presentation of the results and to aid comparison with other experiments, we present below separate analyses for the one-handed and the two-handed groups in Experiment 3.

For <u>one-handed exploration of across stimuli</u>, regularity-type was significant for both RT [F(1,15) = 5.81, p = .029, partial η^2 = .29], and errors [F(1,15) = 6.15, p = .025, partial η^2 = .29]. Detection was easier for symmetry (9.8s, 21%) than repetition (11.5s, 28%). Objectness was significant for both RT [F(1,15) = 24.25, p < .001, partial η^2 = .62], and for errors [F(1,15) = 17.35, p = .001, partial η^2 = .54]. Detection was easier for one-object stimuli (9.4s, 14%) than two-objects stimuli (11.9s, 34%). The interaction of regularity-type x objectness was not significant for RT [F(1,15) = 2.36, p = .15, partial η^2 = .14], or for errors [F(1,15) = 1.35, p = .26, partial η^2 = .08], see Figure 10.

For <u>two-handed exploration of across stimuli</u>, regularity-type was not significant for either RT [F(1,15) = 3.74, p = .072, partial η^2 = .20], or errors [F(1,15) = 3.22, p = .093, partial η^2 = .18]. The two trends went in opposite directions, with symmetry (14.4s, 30%) being detected somewhat faster but less accurately than repetition (15.9s, 23%). Objectness was significant for RT [F(1,15) = 27.17, p < .001, partial η^2 = .64], but not for errors [F(1,15) = 1.45, p = .25, partial η^2 = .09]. Detection was faster for one-object stimuli (14.0s, 23%) than two-objects stimuli (16.3s, 30%). The interaction of regularity-type x objectness was not significant for RT [F(1,15) = 2.09, p = .17, partial η^2 = .12], or for errors [F(1,15) = 0.58, p = .46, partial η^2 = .04], see Figure 10.

Importantly, Experiment 3 replicated Experiment 1 in finding no regularity-type by objectness interaction for the haptic detection of regularities. As in Experiment 1, both the factors of regularity-type and of objectness individually influenced performance, so the lack of interaction between them was not because our manipulations were ineffective. These results extend our findings for haptic free-exploration in Experiment 1 to one-handed and two-handed exploration. We found a clear one-object advantage for repetition detection in haptics which contrasts to the strong two-objects advantage for repetition detection that we obtained for the same task, using the same stimuli, but presented visually, in Experiment 2. Thus, the influence of objectness on regularity detection differed across vision and touch, suggesting that what it means to be an object may differ across the two modalities.

Second, the results of Experiment 3 revealed that varying how stimuli are explored haptically influences the perception of regularities. They further suggest that, in Experiment 1, for stimuli with the axis of regularity running across the body midline, free exploration was mainly performed one-handed. This conclusion is based on the similarity of performance for free-exploration, in Experiment 1, and for one-handed exploration, in Experiment 2 (compare the right side of Figure 5 to the left side of Figure 10). In particular, the one-handed exploration group found it easier to detect symmetry than repetition. This replicates the symmetry advantage for free exploration of both aligned and across stimuli for haptic regularity detection (Experiment 1) and for visual regularity detection (Experiment 2) and it contrasts to the lack of an overall symmetry advantage for two-handed exploration of across stimuli (see the right side of Figure 10). We speculate that this is because, first, two-handed exploration may itself be used as a cue for the presence of two objects (see Lawson et al., in press, for further evidence) and, second, because the body-midline cannot easily be used as a reference frame for detecting symmetry in across stimuli. This latter claim is consistent with the proposal by Ballesteros and colleagues that, for two-handed exploration, symmetry may be easier to detect for stimuli aligned to the body midline (Ballesteros et al, 1997; Ballesteros & Reales, 2004). We suggest that only by acting together do these two effects, of exploration style and of axis of regularity, manage to overcome the usual, powerful advantage for symmetry detection over repetition detection.

Experiment 4

In Experiment 2 photos of the stimuli were taken from slanted views because we wanted to enhance their perception as 3D objects (see also Koning & Wagemans, 2009). However, this manipulation altered image-based aspects of the stimuli, relative to frontoparallel views. In particular, both the distance between the critical contours and the relative position of the vertices along these contours were changed. Importantly, as detailed below, the effects of these image-based changes varied with both regularity-type and with stimulus alignment (van der Vloed et al., 2005). Given the influence on regularity detection of proximity (Csathó, van der Vloed & van der Helm, 2003), and distance between critical lines (Lawson et al., in press), these changes between slanted and frontoparallel views might have influenced the crucial regularity-type by objectness interaction in Experiment 2.

In particular, the use of slanted views might have caused the unexpected advantage which we found for detecting visual regularities when the axis of regularity ran across the body midline. In Experiment 2, for aligned stimuli there was little image-based change to symmetry or to repetition for slanted relative to frontoparallel views (see Figure 11). In contrast, for across stimuli, relative to the frontoparallel view, the slanted view greatly reduced the distance between matched vertices for both symmetrical and repeated contours. In addition, the lines joining these matched vertices were no longer parallel, unlike for frontoparallel views, see Figure 11. Reducing the separation of the critical contours is likely to have aided regularity detection for slanted views of across stimuli (Lawson et al., in press; see also Csathó et al., 2003). As discussed in the introduction, Baylis and Driver (1994) reported that visual symmetry was easier to detect for aligned compared to across 2D stimuli, and this result has been extended to symmetry detection for other, non-frontoparallel depth planes (Farell, 2015) and to haptic regularity detection (Lawson et al., in press). We had therefore expected to replicate this alignment advantage in Experiment 2 but instead we found an unexpected across advantage.

Experiment 4 was conducted to test whether this surprising across advantage could have been caused by the use of slanted views in Experiment 2. In Experiment 4, we showed photos of the same stimuli as in Experiment 2, but the photos were taken from directly above the stimuli, so showed a frontoparallel view (see Figure 11). In these frontoparallel views, unlike slanted views, the relative position of vertices and the distance between the pairs of critical contours was the same for across and aligned stimuli. If the advantage for across relative to aligned stimuli in Experiment 2 resulted from image-based distortions due to the use of slanted views then this advantage should disappear when frontoparallel views were presented in Experiment 4. This, in turn, would provide further evidence that distance between critical contours or lines is an important factor in the detection of visual regularities (see also Lawson et al., in press). It is important to check this possibility since a similar issue (an unintended change in the image-based distance between critical contours) also arose for the slanted view stimuli used by Koning and Wagemans (2009), and because this effect is commonplace in everyday life, when we see multiple, similarly-shaped objects lined up behind each other (see Figure 2 for examples).

Method

Participants The same 32 participants who took part in Experiment 3 participated 2-10 days later in Experiment 4. They all had normal or corrected to normal vision.

Materials, Design and Procedure These were identical to Experiment 2 except as noted below. A new set of 320 photos were taken of the stimuli used in Experiment 1. These photos were taken using the same conditions and procedure as for the central photos used in Experiment 2 (see Figure 6) except that the camera was positioned directly above the centre of the stimuli, at an angle of 90° to the plane of the stimuli (see Figure 11). All stimuli were presented on a monitor with a resolution of 1280 x 1024 pixels at a refresh rate of 60 Hz. The 3D shutter glasses were not used. One participant was inadvertently run in the wrong counterbalancing order condition (beginning with the aligned sub-block rather than the across sub-block). The experiment took around forty minutes.

Results and Discussion

Appendix 4 presents the full ANOVAs for RT, errors and sensitivity (d') for Experiment 4. As in the previous experiments, we focus here on the two most important interactions. All pairwise differences noted below were significant ($p < .05$) in post-hoc Newman-Keuls analyses.

First, the interaction of regularity-type x objectness was significant for both RT [$F(1,31) = 91.66$, $p < .001$, partial $\eta^2 = .75$], and errors [$F(1,31) = 32.25$, $p < .001$, partial $\eta^2 = .51$]. Symmetry detection was not significantly different between one-object (0.82s, 3%) and two-objects (0.83s, 3%) stimuli. However, repetition detection was both slower and less accurate for one-object (1.31s, 17%) compared to two-objects (1.10s, 6%) stimuli.

Second, unlike in Experiment 2, the interaction of regularity-type x alignment was not significant for either RT [$F(1,31) = 2.48$, $p = .125$, partial $\eta^2 = .07$], or for errors [$F(1,31) = .40$, $p = .53$, partial $\eta^2 = .01$]. This suggests that the alignment advantage for symmetry detection and the alignment cost for repetition detection found in Experiment 2 were both due to the image-based distortions in the slanted views used in Experiment 2, see Figure 11.

To simplify presentation of the results, and to aid comparison with other experiments, we present below separate analyses for the aligned and the across stimuli.

For aligned stimuli, regularity-type was significant for both RT [$F(1,31) = 86.74$, $p < .001$, partial $\eta^2 = .74$], and errors [$F(1,31) = 43.21$, $p < .001$, partial $\eta^2 = .58$]. Detection was easier for symmetry (0.78s, 3%) than repetition (1.19s, 11%). Objectness was significant for both RT [$F(1,31) = 24.62$, $p < .001$, partial $\eta^2 = .44$], and errors [$F(1,31) = 32.59$, $p < .001$, partial $\eta^2 = .51$]. Detection was harder for one-object stimuli (1.03s, 10%) than two-objects stimuli (0.95s, 4%). Finally the interaction of regularity-type x objectness was significant for both RT [$F(1,31) = 45.11$, $p < .001$, partial $\eta^2 = .59$], and errors [$F(1,31) = 47.14$, $p < .001$, partial $\eta^2 = .60$], see Figure 12. Symmetry detection was not significantly different between one-object (0.76s, 2%) and two-objects (0.80s, 3%) stimuli. In contrast, repetition detection was both slower and less accurate for one-object (1.29s, 18%) compared to two-objects (1.09s, 4%) stimuli.

For across stimuli, regularity-type was significant for both RT [$F(1,31) = 68.29$, $p < .001$, partial $\eta^2 = .69$], and errors [$F(1,31) = 43.17$, $p < .001$, partial $\eta^2 = .58$]. Detection was easier for symmetry (0.87s, 3%) than repetition (1.22s, 12%). Objectness was significant for both RT [$F(1,31) = 36.71$, $p < .001$, partial $\eta^2 = .54$], and errors [$F(1,31) = 19.22$, $p < .001$, partial $\eta^2 = .38$]. Detection was harder for one-object stimuli (1.10s, 10%) than two-objects stimuli (0.99s, 5%). Finally the interaction of regularity-type x objectness was significant for both RT [$F(1,31) = 68.47$, $p < .001$, partial $\eta^2 = .69$], and errors [$F(1,31) = 4.77$, $p = .037$, partial $\eta^2 = .13$], see Figure 12. Symmetry detection was not significantly different between one-object (0.87s, 4%) and two-objects (0.86s, 2%) stimuli. In contrast, repetition detection was both slower and less accurate for one-object (1.33s, 16%) compared to two-objects (1.11s, 9%) stimuli. Thus the pattern of results was the same for aligned and for across stimuli.

First, replicating Experiment 2, in Experiment 4 we found an overall advantage for detecting symmetry compared to repetition, consistent with the usual finding in vision. Second, importantly, we replicated the interaction of regularity-type by objectness that we obtained in Experiment 2. Once again, visual repetition detection was much easier for two-objects than for one-object stimuli. Third, we found an overall advantage for aligned compared to across stimuli, see Appendix 4. This suggests that the unexpected advantage found for across stimuli in Experiment 2 resulted from presenting slanted views which inadvertently confounded the effects of axis of regularity and regularity-type with image-based distortions that altered the pictorial separation of the critical contours. This finding provides further evidence that line or contour separation influences regularity detection (Csathó et al., 2003; Lawson et al., in press). We suggest that similar effects may have influenced performance for the slanted stimuli used by Koning and Wagemans (2009). This highlights the trade-off that occurs when presenting slanted views, namely that, although such views may reduce the ambiguity of figure-ground assignment, this comes at a cost of image-based distortions.

General Discussion

Despite the long history of research into our ability to detect visual regularities, it is still not fully clear why we are generally better at detecting symmetry than repetition, and why there is usually a one-object advantage for detecting symmetry but a two-objects advantage for detecting repetition. In the present studies we aimed to provide converging evidence about the underlying reasons for these differences. We compared regularity detection by active touch (haptics) and by vision with the overarching aim of investigating the nature of objectness for vision and touch.

We conducted two haptic and two visual experiments. Across the two modalities we used the same participants, the same regularity detection tasks and we presented matched stimuli. For vision, in Experiments 2 and 4, we found similar results to previous research (Baylis & Driver, 1994; Bertamini, 2010; Bertamini et al., 1997; Friedenberg & Bertamini, 2000; Koning & Wagemans, 2009). There was a general advantage for detecting symmetry relative to repetition and, most importantly, an interaction between the effects of regularity-type and objectness. In every condition tested there was a one-object cost for repetition detection, whilst for symmetry detection performance was similar for one-object and two-objects stimuli. This was the case whether the axis of regularity ran across, or was aligned with, the body midline, and whether stimuli were presented pictorially or stereoscopically, and whether stimuli were photographed from a slanted or a frontoparallel view. These results are consistent with the claim that, for vision, repetition provides a cue to the presence of multiple objects and so repetition is easier to detect across pairs of critical contours which belong to two different objects, rather than to two sides of the same object.

In contrast, for haptics, although the factors of regularity-type and objectness were, individually, significant in both Experiments 1 and 3, we found no interaction between them in any condition. Crucially, in no case did we obtain the two-objects advantage for repetition detection that was found so reliably for visually presented stimuli. Instead, for haptics, for across stimuli, there was a one-object advantage for detecting both symmetry and repetition (regardless of whether exploration was free, or was restricted to be either one-handed or two-handed), whilst for aligned stimuli there was no effect of objectness on regularity detection.

Regularity detection thus differed reliably across vision and haptics. This, in turn, suggests that the influence of regularity-type and objectness on regularity detection depends on modality-specific processes, rather than solely on physical properties of our external world. In particular, these results are not consistent with the explanation of the regularity-type by objectness interaction for vision as arising solely from properties of 3D objects, with symmetry being associated with the presence of a single object and repetition being associated with the presence of multiple objects. This is because any such associations should be universal properties of the external world. This account should therefore predict that these associations would provide equally useful cues to objectness for vision and for touch, and so the two modalities should respond to regularities in similar ways. We are not suggesting that objectness does not matter. Rather, we believe that our results indicate that the nature of objects, and the cues used to define objects, may differ for vision and for touch.

Enquist and Arak (1994) noted that humans like symmetrical biological signals (such as flowers and butterflies) even though these signals arise from independently evolved organisms that experience the world in different ways than we do. Enquist and Arak suggested that regularity detection may universally benefit the perception of objects in the external world. A strong version of this argument would suggest that sensitivity to regularities should be similar across different modalities within an organism, as well as across different species. In particular, it predicts that the same regularity-type by objectness interaction should be found for vision and touch. This was not what we found here. We propose that, instead, regularity detection can be used to inform us about differences in how our sensory systems acquire and process information, as well as about the presence, shape and location of objects in the external world. We further suggest that what it means to be an object differs for haptics and vision, with different cues to objectness varying in their importance. Feldman (2003) has argued that it is extremely difficult to provide a formal definition of a visual object whilst, as far as we are aware, nobody has attempted to define a haptic object (Lawson et al., in press). The present study does not provide sufficient empirical evidence to allow us to specify the nature of haptic objects, but we propose that comparing regularity detection across vision and touch provides a powerful way to examine which cues are used by each modality.

Our finding, that the same factors have different effects on regularity detection for vision and for haptics, leaves open many questions for future research. It might be that these differences arise because haptics and vision process regularities in irreconcilably different ways. Alternatively, these differences could reflect differences in information acquisition. For example, vision usually allows us to process the whole of an object simultaneously and quickly, whereas haptics typically requires slower, serial accumulation of local information which needs to be integrated over time to create a global percept. One way to investigate whether differences in how information is acquired across modalities cause differences in regularity detection is to more closely match visual to haptic exploration. For example, visual stimuli could be shown through a small aperture to force information to be extracted more slowly and sequentially (e.g., see Craddock, Martinovic & Lawson, 2011; Martinovic, Lawson & Craddock, 2012). Using this approach, we have found that visual regularity detection using an aperture eliminated the usual regularity-type by objectness interaction (Cecchetto & Lawson, in preparation). Instead, we obtained a one-object advantage for detecting visual repetition as well as for detecting visual symmetry, thus replicating the results obtained in Experiments 1 and 3 here for haptics. This, in turn, suggests that the memory burden imposed on haptics by its slow, serial acquisition of information may be the cause of a specific cost on repetition detection across multiple objects (see also Cecchetto & Lawson, 2015).

In summary, in this study we found a general advantage for detecting symmetry compared to repetition for haptics as well as for vision. However, for most other comparisons we found that regularity detection differed across the modalities. Most importantly, for vision we found an interaction between regularity-type and objectness, with a two-objects advantage for repetition detection. In contrast, for haptic regularity detection there was either a one-object advantage (for across stimuli) or no effect of objectness (for aligned stimuli). In addition, stimulus orientation with respect to the body midline (aligned or across) and modality-specific factors (visual perspective: slanted or frontoparallel; and the nature of haptic exploration: one-handed versus two-handed) also influenced regularity detection. Thus, both the manner of stimulus presentation, and the acquisition of information affected regularity detection. These results provide evidence against the claim that regularity detection simply reflects extrinsic, universal properties of our physical environment, since the 3D objects which generated the input stimuli were constant across all of these manipulations. Our results instead indicate that how we acquire information, and how we explore our environment, has a powerful, modality-specific impact on our perception of regularities.

FOOTNOTES

1 There is a further issue to consider regarding the interpretation of these previous findings. Van der Helm and Treder (2009) noted that most previous studies investigating the role of objectness on regularity detection tested anti-repetition, rather than true repetition. Bertamini et al. (1997), Bertamini (2010), Friedenberg and Bertamini (2000) and Koning and (Wagemans, 2009) all presented shapes where the two critical contours for repetition stimuli had opposite polarities in terms of concavities and convexities (defined with respect to the object) and in terms of colour and luminance (of the object relative to its background). For simplicity, and for consistency with the previous literature, we have described our stimuli as repetition, rather than anti-repetition, stimuli. In other studies we have addressed this issue directly, by comparing visual and haptic regularity detection for repetition versus anti-repetition stimuli (Cecchetto & Lawson, under review) and for line only stimuli (Lawson, Ajvani & Cecchetto, in press).

2 In the present experiments we manipulated the alignment of the axis of regularity in both vision and touch. We used two orthogonal axis directions. Consistent with most previous research, these both lay in the horizontal plane of a table-top for haptics, and in the vertical plane of a computer monitor for vision. To allow us to use the same terms for both modalities and, to avoid confusion, we have not used horizontal and vertical to refer to the orientation of these axes. Instead, we describe them as being either aligned with, or running across, the participant's body midline.

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FIGURES

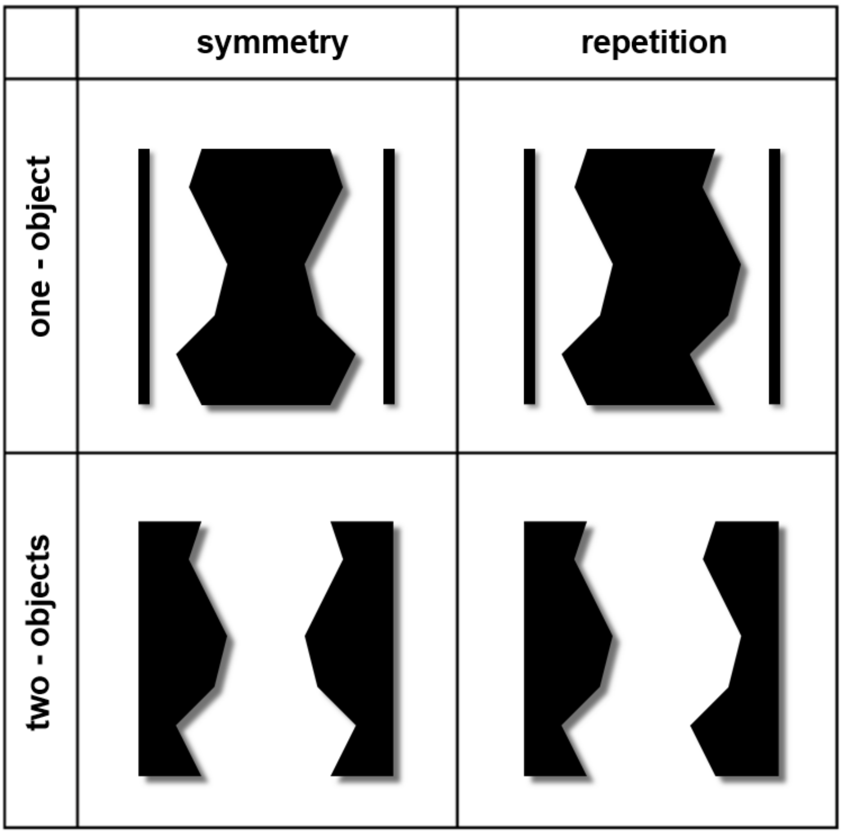


Figure 1. Examples of regular, one-object (top row) and two-objects (bottom row) stimuli, with symmetrical (left side) and repeated (right side) pairs of critical contours. These stimuli are similar to those used in the present study. The critical contours comprised the left and right sides of one-object stimuli and the facing sides of two-objects stimuli. The pairs of vertical lines flanking the central object in the one-object stimuli ensured that the overall width of these stimuli matched that of the two-objects stimuli. Stimuli adapted from Koning and Wagemans (2009).

Figure 2. Illustrations of regularities in our environment. The top three images show image-based repetition, with multiple, similarly-shaped objects, lined up and receding in depth. Note that each individual item in the set (pillars, bicycles and sea-kayaks) is an approximately symmetrical 3D object. We often also encounter single symmetrical stimuli, such as a bicycle with no other bicycles nearby. In contrast, repetition within an object is rare; three examples are shown in the bottom row of images, of a glacier, a snake and a curtain (a cave formation).

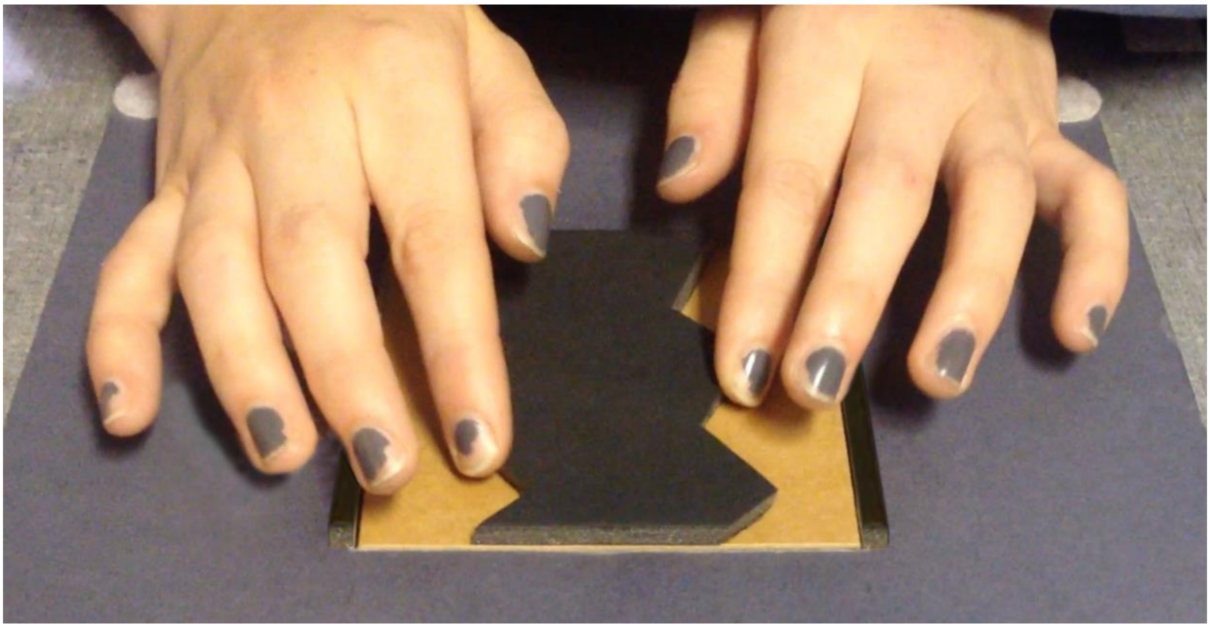


Figure 3. A participant feeling a repeated, aligned, one-object stimulus in Experiment 1.

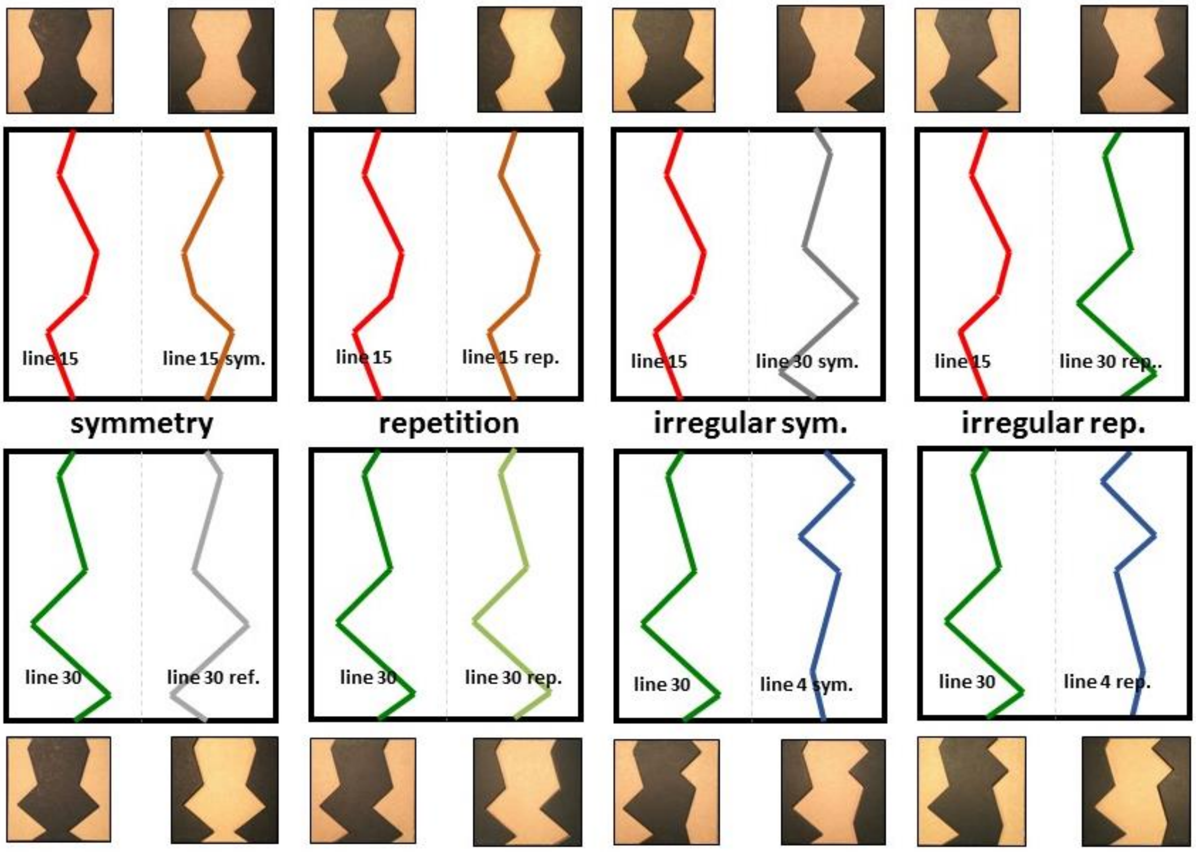


Figure 4. An illustration of how sets of stimuli were created for two of the 40 critical contours (line 15 and line 30). In the top half of the figure, line 15 was mirror-reflected and translated to produce the symmetrical and repeated stimuli respectively. Line 15 was also paired with a symmetrical and a repeated version of line 30 to create the irregular symmetrical and irregular repeated stimuli respectively. In the bottom half of the figure the same procedure was used to create the stimuli based on line 30, but here the irregular stimuli used pairings with line 4. Finally, for each pair of critical contours, two stimuli were created, as shown on the top and the bottom rows. These comprised the one-object stimuli (the central, black object flanked by a lighter background in the left photo of each pair) and the two-objects stimuli (the two black objects are separated by a lighter, central background shown in the right photo of each pair).

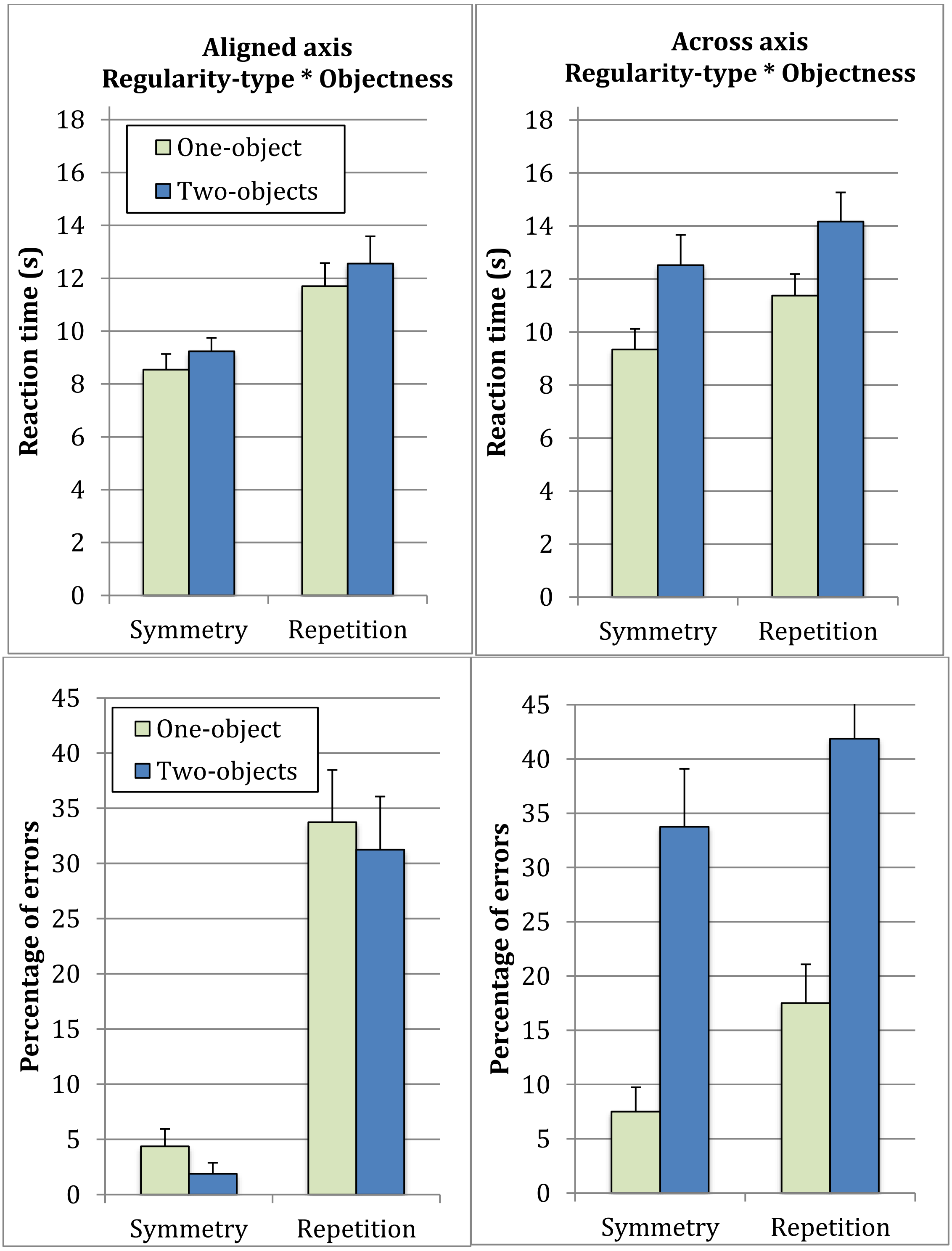


Figure 5. Results for regular trials for the haptic detection of regularities in Experiment 1. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark bars) stimuli with the axis of regularity aligned with (left graphs) or running across (right graphs) the body midline. Error bars represent one standard error of the mean.

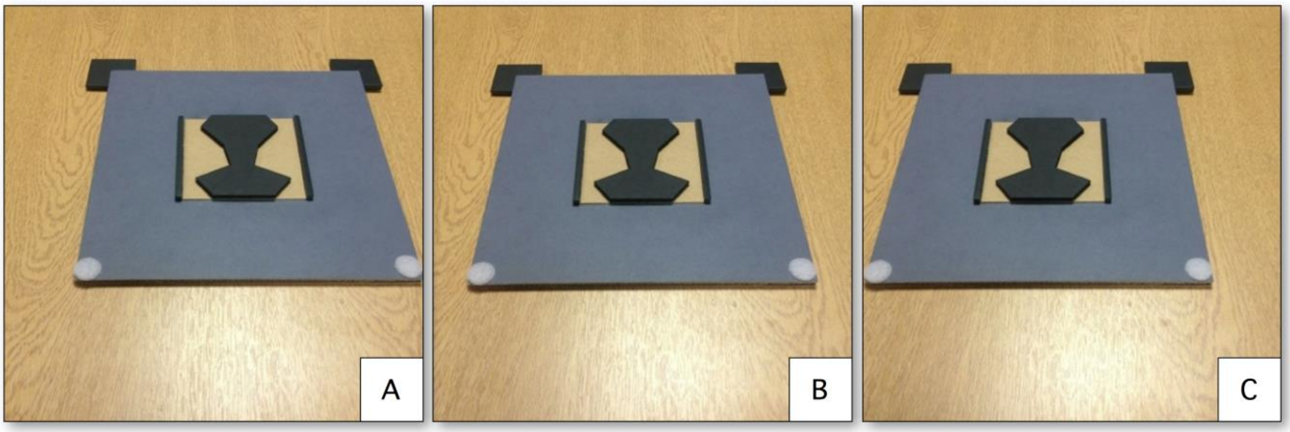


Figure 6. Slanted-view photos of the same symmetrical, one-object stimulus with the axis of regularity aligned to the body midline. Photos were taken from three different positions: A) left eye; B) central; C) right eye. Photos A and C were taken by translating the camera 3cm left and right respectively from the central position. In Experiment 2, photos A and C were presented to the left and right eyes respectively on stereoscopic trials, whilst photo B was presented to both eyes on pictorial trials.

Figure 7. An example of a symmetrical, two-objects stimulus aligned to the body midline and displayed pictorially on the monitor in Experiment 2.

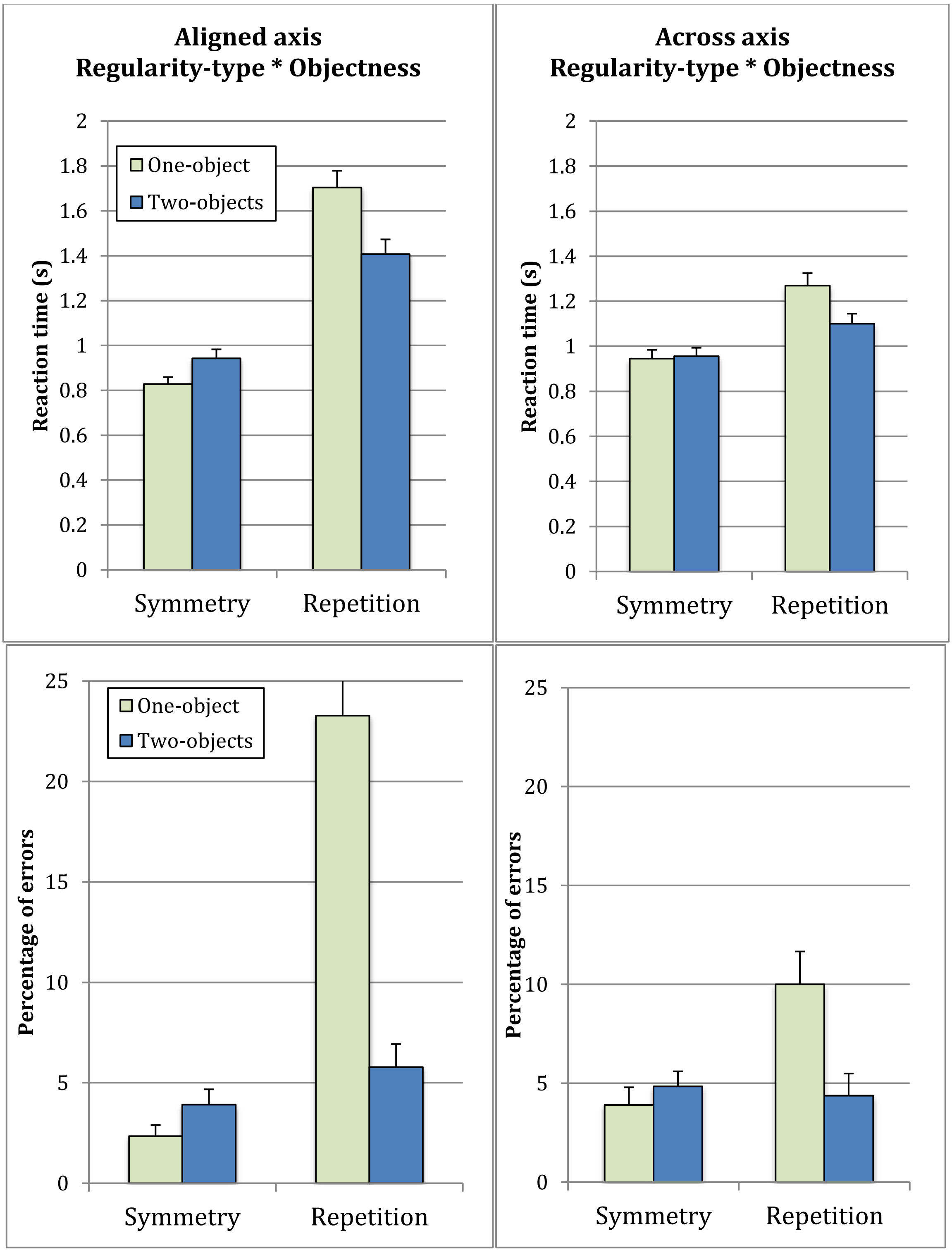


Figure 8. Results for regular trials for the visual detection of slanted views of regularities in Experiment 2. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark bars) stimuli with the axis of regularity aligned with (left graphs) or running across (right graphs) the body midline. Error bars represent one standard error of the mean.

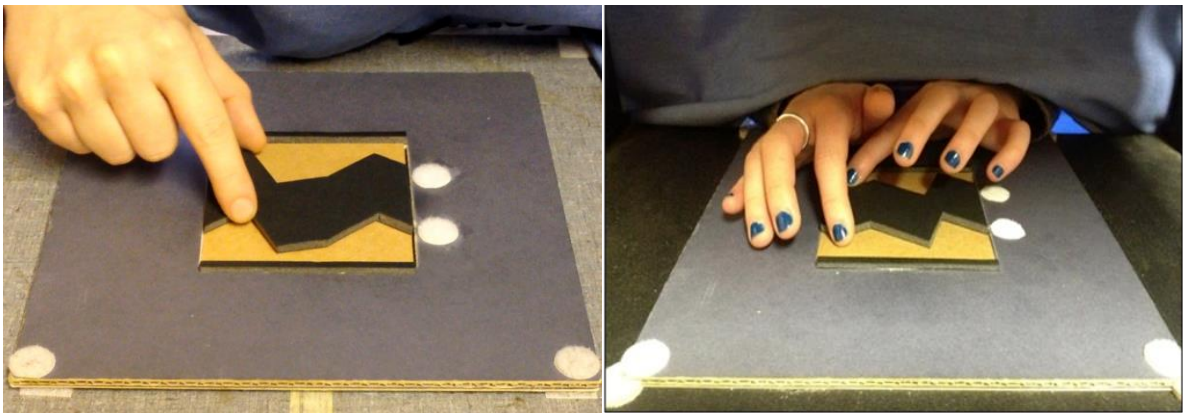


Figure 9. One-handed (left) versus two-handed (right) exploration conditions in Experiment 3. The stimuli were identical to those used in Experiment 1 except that the axis of regularity always ran across the participant's body midline. The resting positions, marked by two white round patches, were placed on the left side of the stimuli (from the participant's perspective; shown on the right side of the photos here).

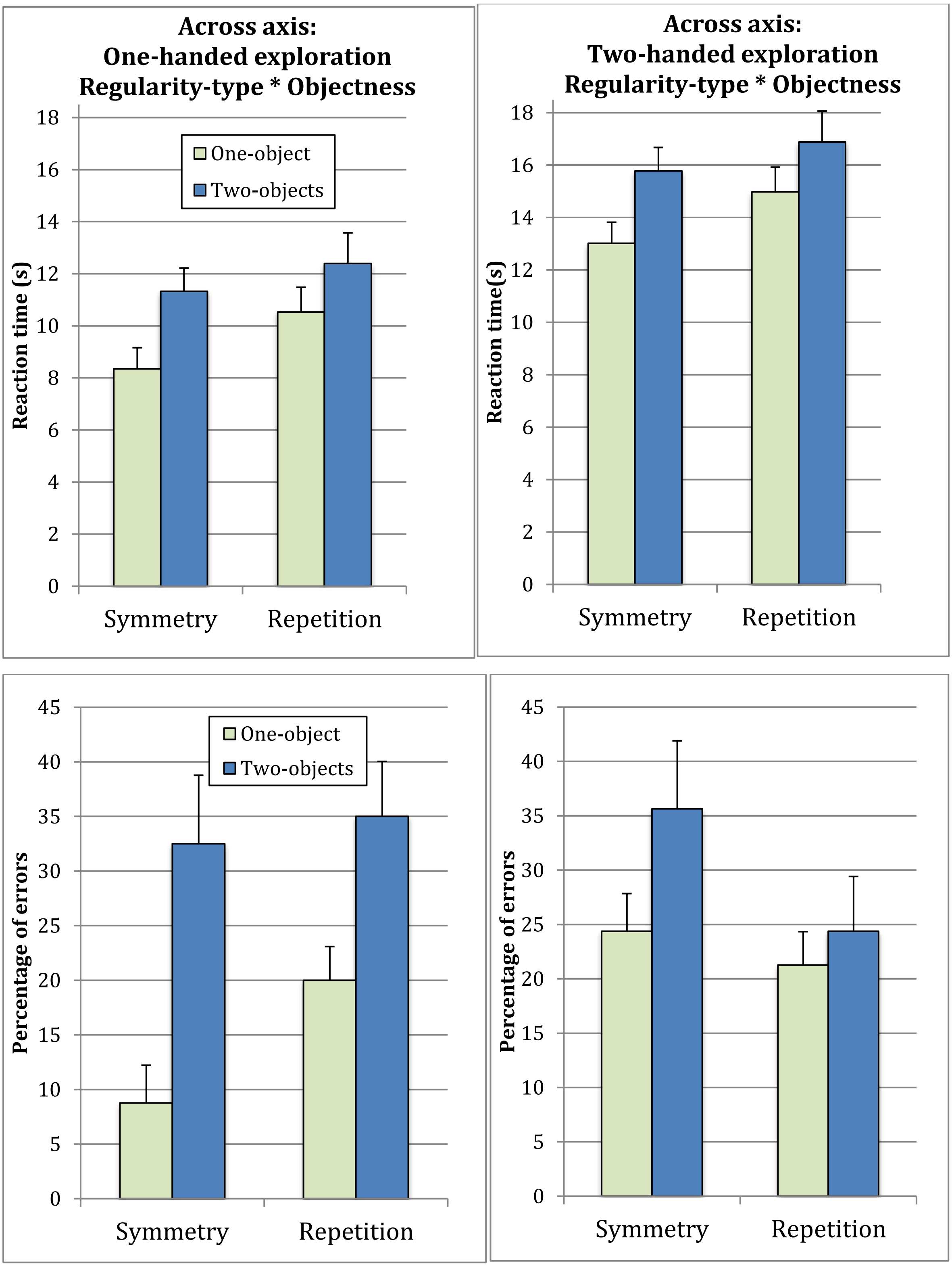


Figure 10. Results for regular trials, with the axis of regularity running across the body midline, for the haptic detection of regularities in Experiment 3. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark bars) stimuli explored with one hand (left graphs) or with two hands (right graphs). Error bars represent one standard error of the mean.

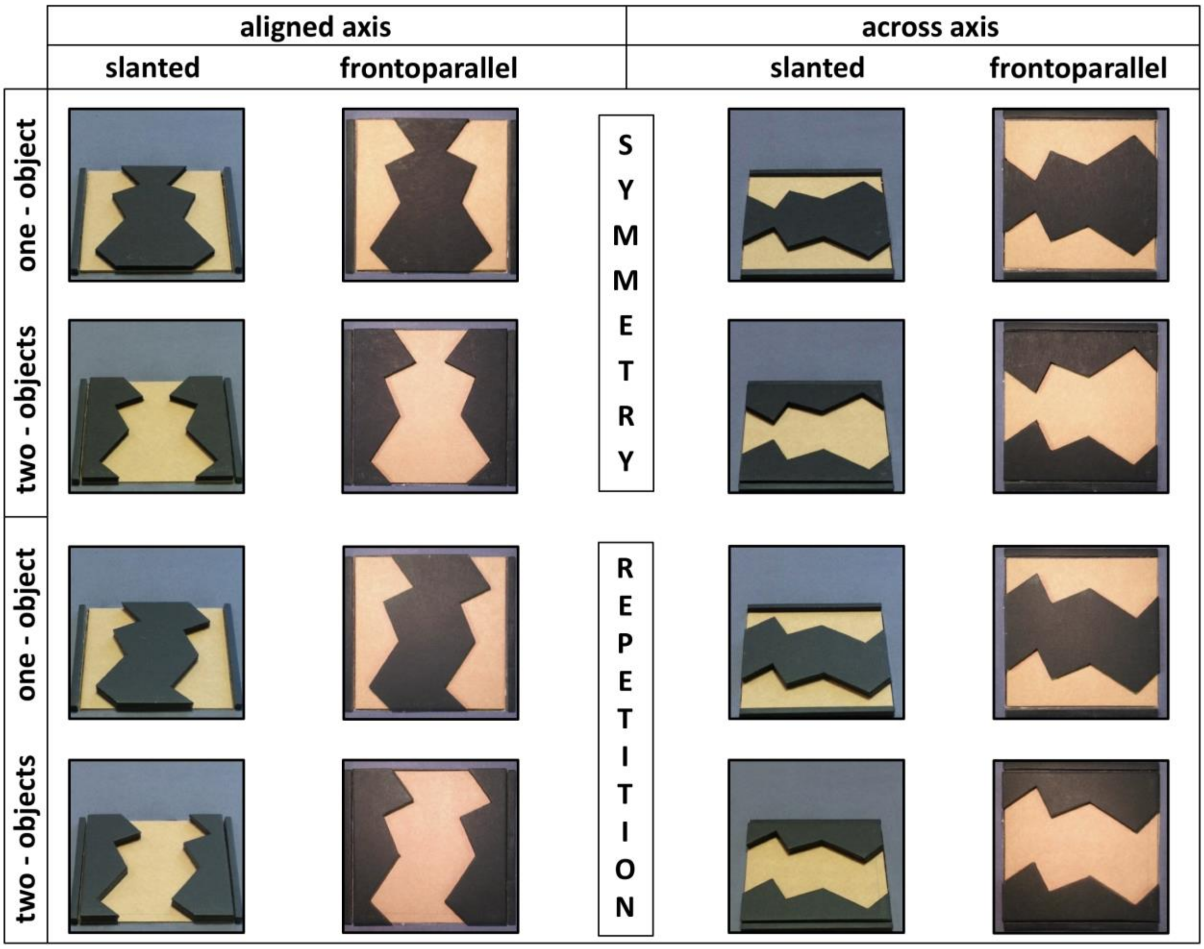
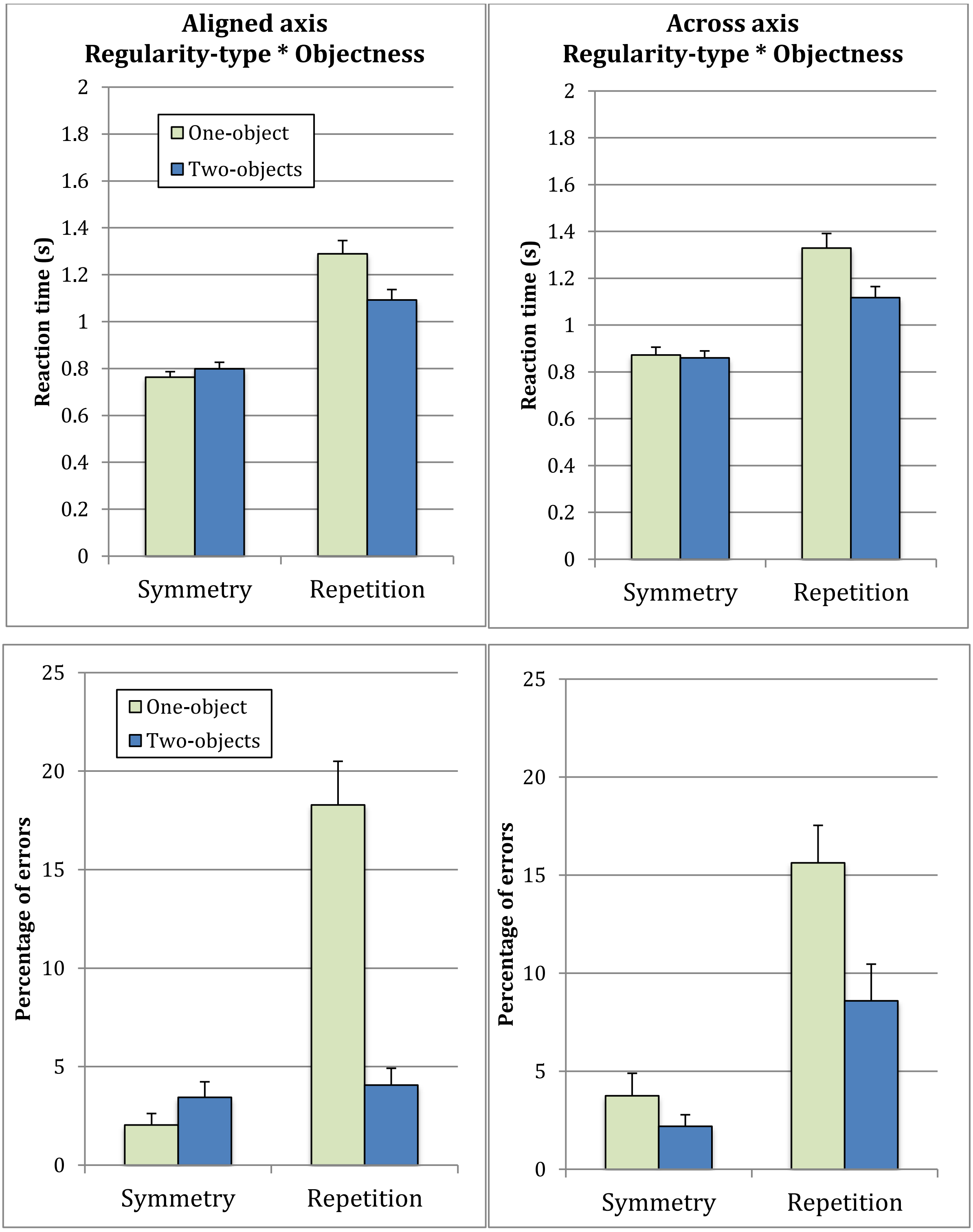


Figure 11. An illustration of the differences between the slanted views used in Experiment 2 and the frontoparallel views used in Experiment 4. All photos are scaled to equate the length at the base of the frame. The change in the location of the vertices in slanted views relative to frontoparallel views depends on the alignment of the axis of regularity of the stimuli. The aligned, slanted photos (first column) retain perfect symmetry, but have somewhat distorted repetition relative to frontoparallel views (second column). The across, slanted stimuli (third column) have both distorted symmetry and distorted repetition relative to frontoparallel views (fourth column). This latter pattern of distortions also occurred for the slanted stimuli used by Koning and Wagemans (2009) and van der Vloed et al. (2005). Note, too, that the distance between the two critical contours reduced less for slanted compared to frontoparallel views for aligned stimuli (comparing the left two columns) than for across stimuli (comparing the right two columns). The opposite occurred for the length of the critical contours. This length was reduced more for slanted compared to frontoparallel views for aligned stimuli than for across stimuli.


Aligned axis
Regularity-type * Objectness

Across axis
Regularity-type * Objectness

Figure 12. Results for regular trials for the visual detection of frontoparallel views of regularities in Experiment 4. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark bars) stimuli with the axis of regularity aligned with (left graphs) or running across (right graphs) the body midline. Error bars represent one standard error of the mean.

APPENDIX 1 - Results for Experiment 1

ANOVAs were conducted on RT and percentage of errors for regular trials and on sensitivity (d') for all trials. In the ANOVAs there were two within-subjects factors: regularity-type (symmetry or repetition) and objectness (one-object or two-objects) and one between-subjects factor of alignment (axis of regularity aligned with, or running across, the participant's body midline).

The main effects are reported first. Regularity-type was significant for RT [$F(1,30) = 28.80$, $p < .001$, partial $\eta^2 = .49$], errors [$F(1,30) = 65.61$, $p < .001$, partial $\eta^2 = .69$], and sensitivity [$F(1,30) = 102.23$, $p < .001$, partial $\eta^2 = .77$]. Detection was easier for symmetry (9.9s, 12%, d' of 2.15) than repetition (12.4s, 31%, 1.03). Objectness was significant for RT [$F(1,30) = 28.87$, $p < .001$, partial $\eta^2 = .49$], errors [$F(1,30) = 13.05$, $p = .001$, partial $\eta^2 = .30$], and sensitivity [$F(1,30) = 23.06$, $p < .001$, partial $\eta^2 = .44$]. Detection was easier for one-object (10.2s, 16%, d' of 1.81) than two-objects (12.1s, 27%, 1.37) stimuli. Alignment was not significant for RT [$F(1,30) =1.58$, $p = .22$, partial $\eta^2 = .05$], but it was for errors [$F(1,30) = 4.97$, $p = .033$, partial $\eta^2 = .14$], and sensitivity [$F(1,30) = 8.68$, $p = .006$, partial $\eta^2 = .22$]. Detection was more accurate and more sensitive for aligned (10.5s, 18%, d' of 1.77) than across (11.8s, 25%, 1.41) stimuli.

Next the interactions are reported. Importantly, the main interaction of interest, regularity-type x objectness was not significant for RT [$F(1,30) = 0.35$, $p = .86$, partial $\eta^2 = .001$], or errors [$F(1,30) = 0.06$, $p = .82$, partial $\eta^2 = .00$], or sensitivity [$F(1,30) = 2.07$, $p = .16$, partial $\eta^2 = .07$]. There was always an advantage for detecting regularities on one-object trials, and it was similar in size for symmetry (one-object: 8.9s, 6%, d' of 2.45; two-objects: 10.9s, 18%, 1.84) and repetition (one-object: 11.5s, 26%, 1.17; two-objects: 13.4s, 37%, 0.90) detection. Thus, unlike visual regularity detection, in haptics there was no evidence of a two-objects advantage for repetition. The interaction of regularity-type x alignment was not significant for RT [$F(1,30) = 2.18$, $p = .15$, partial $\eta^2 = .07$], but it was for errors [$F(1,30) = 18.32$, $p < .001$, partial $\eta^2 = .38$], and sensitivity [$F(1,30) = 15.90$, $p < .001$, partial $\eta^2 = .35$]. Unexpectedly, the interaction of objectness x alignment was significant for RT [$F(1,30) = 9.98$, $p = .004$, partial $\eta^2 = .25$], errors [$F(1,30) = 19.39$, $p < .001$, partial $\eta^2 = .39$], and sensitivity [$F(1,30) = 29.20$, $p < .001$, partial $\eta^2 = .44$]. Detection was much worse for two-objects across stimuli (13.3s, 38%, d' of 0.93) than the three other conditions: one-object across (10.4s, 13%, 1.88), two-objects aligned (10.9s, 17%, 1.80) and one-object aligned (10.1s, 19%, 1.75) stimuli. No other differences were significant. Finally, the three-way interaction of regularity-type x objectness x alignment was not significant for RT [$F(1,30) = 0.25$, $p = .62$, partial $\eta^2 = .01$], errors [$F(1,30) = 0.55$, $p = .82$, partial $\eta^2 = .00$], or sensitivity [$F(1,30) = 1.43$, $p = .24$, partial $\eta^2 = .05$], see Figure 5.

APPENDIX 2 - Results for Experiment 2

ANOVAs were conducted on RT and percentage of errors for regular trials and on sensitivity (d') for all trials. In the ANOVAs there were four within-subjects factors: regularity-type (symmetry or repetition), objectness (one-object or two-objects), alignment (axis of regularity aligned with or running across the participant's body midline) and visual presentation (pictorial or stereoscopic).

Visual presentation was not significant for RT [$F(1,31) = 1.76$, $p = .20$, partial $\eta^2 = .05$], or errors [$F(1,31) = 0.21$, $p = .66$, partial $\eta^2 = .00$], or sensitivity [$F(1,31) = 0.05$, $p = .82$, partial $\eta^2 = .00$]. Results were similar for pictorial (1.13s, 8%, d' of 2.58) and stereoscopic (1.16s, 7%, 2.59) presentation. The only interaction involving visual presentation was the three-way interaction of visual presentation x regularity-type x objectness, and that was only significant for RT [$F(1,31) = 4.88$, $p = .035$, $\eta_p^2 = .14$], not for errors [$F(1,31) = 0.11$, $p < .916$, $\eta_p^2 = .00$], or sensitivity [$F(1,31) = 1.07$, $p = .31$, partial $\eta^2 = .03$]; this interaction could not be readily interpreted. Thus enhancing the 3D interpretation of the stimuli to reduce figure-ground ambiguity by presenting stimuli stereoscopically did not influence regularity detection.

The other main effects are now reported. Regularity-type was significant for RT [$F(1,31) = 92.15$, $p < .001$, $\eta_p^2 = .75$], errors [$F(1,31) = 47.83$, $p < .001$, partial $\eta^2 = .61$], and sensitivity [$F(1,31) = 67.84$, $p < .001$, partial $\eta^2 = .69$]. Consistent with previous research, symmetry (0.92s, 4%, d' of 2.87) was easier to detect than repetition (1.37s, 11%, 2.30). Objectness was also significant for RT [$F(1,31) = 51.15$, $p < .001$, partial $\eta^2 = .62$], errors [$F(1,31) = 61.72$, $p < .001$, partial $\eta^2 = .67$], and sensitivity [$F(1,31) = 8.17$, $p = .008$, partial $\eta^2 = .21$]. Two-objects stimuli (1.10s, 5%, d' of 2.63) were easier to detect than one-object stimuli (1.19s, 10%, 2.54). Alignment was significant for RT [$F(1,31) = 27.67$, $p < .001$, partial $\eta^2 = .47$], errors [$F(1,31) = 21.68$, $p < .001$, partial $\eta^2 = .41$], and sensitivity [$F(1,31) = 21.95$, $p < .001$, partial $\eta^2 = .42$]. Unexpectedly, across stimuli (1.07s, 6%, d' of 2.67) were easier to detect than aligned stimuli (1.22s, 9%, 2.50). This is the reverse of the aligned (vertical) advantage for regularity detection that has typically been reported in the literature. In Experiment 4 we found evidence that this across advantage occurred here in Experiment 2 because slanted rather than frontoparallel views were presented.

Next, the remaining interactions are reported. The interaction of regularity-type x objectness - which was not significant in Experiment 1 for haptics - was found for vision for RT [$F(1,31) = 162.02$, $p < .001$, partial $\eta^2 = .84$], errors [$F(1,31) = 84.19$, $p < .001$, partial η

^{2} =.73], and sensitivity [F(1,31) = 22.96, $p < .001$, partial $\eta^2 = .43$]. There was no significant difference in detecting symmetry with one-object (.89s, 3%, d' of 2.91) compared to two-objects (.95s, 4%, 2.84) stimuli. In contrast, repetition was harder to detect for one-object (1.49s, 17%, d' of 2.18) compared to two-objects (1.26s, 5%, 2.43) stimuli. The interaction of regularity-type x alignment was significant for RT [F(1,31) = 66.82, $p < .001$, partial $\eta^2 = .68$], errors [F(1,31) = 25.27, $p < .001$, partial $\eta^2 = .45$], and sensitivity [F(1,31) = 63.41, $p < .001$, partial $\eta^2 = .67$]. For symmetry it was easier to detect aligned (.89s, 3%, d' of 2.95) compared to across (.95s, 4%, 2.79) stimuli. However for repetition it was harder to detect aligned (1.56s, 15%, d' of 2.05) than across (1.19s, 7%, 2.55) stimuli. The interaction of objectness x alignment was not significant for RT [F(1,31) = 0.11, $p > .74$, partial $\eta^2 = .01$], or for sensitivity [F(1,31) = 0.01, $p = .91$, partial $\eta^2 = .00$], but it was significant for errors [F(1,31) = 9.09, $p < .005$, partial $\eta^2 = .23$]. Errors were greater for one-object, aligned stimuli (1.27s, 13%, d' of 2.46) than for the other three conditions: two-objects aligned (1.18s, 5%, 2.55); one-object across (1.11s, 7%, 2.63); and two-objects across (1.03s, 5%, 2.71). Finally, there was a significant three-way interaction of regularity-type x objectness x alignment for RT [F(1,31) = 29.28, $p < .001$, partial $\eta^2 = .49$], errors [F(1,31) = 26.05, $p < .001$, partial $\eta^2 = .46$], and sensitivity [F(1,31) = 5.99, $p = .02$, partial $\eta^2 = .16$], see Figure 8.

APPENDIX 3 - Results for Experiment 3

ANOVAs were conducted on RT and percentage of errors for regular trials and on sensitivity (d') for all trials. The ANOVAs included the results for the across group in Experiment 1 who did the same task as the two groups in Experiment 3 but who were allowed to freely explore the stimuli. The ANOVAs therefore included three groups of 16 participants. There were two within-subjects factors: regularity-type (symmetry or repetition) and objectness (one-object or two-objects) and one between-subjects factor of exploration (free, one-handed or two-handed).

The main effects are reported first. Regularity-type was significant for RT [$F(1,45) = 17.32$, $p < .001$, partial $\eta^2 =.28$], and sensitivity [$F(1,45) = 15.69$, $p < .001$, partial $\eta^2 =.26$], but not for errors [$F(1,45) = 2.4$, $p = .13$, partial $\eta^2 = .05$]. Detection was faster and sensitivity was greater for symmetry (11.7s, 24%, d' of 1.53) than repetition (13.4s, 27%, 1.19). Objectness was significant for RT [$F(1,45) = 78.43$, $p < .001$, partial $\eta^2 = .64$], errors [$F(1,45) = 30.09$, $p < .001$, partial $\eta^2 = .40$], and sensitivity [$F(1,45) = 32.08$, $p < .001$, partial $\eta^2 =.42$]. Detection was easier for one-object (11.3s, 17%, d' of 1.63) than two-objects (13.8s, 34%, 1.10) stimuli. Exploration was significant for RT [$F(2,45) = 7.57$, $p = .001$, partial $\eta^2 = .25$], but not for errors [$F(2,45) = .23$, $p = .80$, partial $\eta^2 = .01$], or sensitivity [$F(2,45) = 0.18$, $p = .89$, partial $\eta^2 =.01$]. Detection was slower for two-handed exploration (15.2s, 26%, d' of 1.33) than for both free exploration (11.8s, 25%, 1.41) and one handed exploration (10.6s, 24%, 1.35).

Next, the interactions are reported. The interaction of regularity-type x objectness was not significant for RT [F(1,45) = 3.46, p = .07, partial η2 = .07], or for errors [F(2,45) = .05, p = .2, partial η2 = .04], though it was for sensitivity [F(1,45) = 9.96, p = .003, partial η2 = .18]. The one-object advantage for sensitivity was greater for symmetry detection (d' of 1.96 versus 1.10) than for repetition detection (1.29 versus 1.09). Thus, importantly, unlike for visual repetition detection, in Experiments 2 and 4, haptic repetition detection did not produce a two-object advantage, replicating the one-object advantage for haptic repetition detection found in Experiment 1. The interaction of regularity-type x exploration was not significant for RT [$F(2,45) = .05$, $p = .95$, partial $\eta^2 = .00$], but it was for errors [$F(2,45) = 7.32$, $p = .002$, partial $\eta^2 =.25$], and sensitivity [$F(2,45) = 8.67$, $p = .001$, partial $\eta^2 =.28$]. Symmetry was detected more accurately and more sensitively than repetition for free exploration (symmetry: 10.9s, 21%, d' of 1.74; repetition: 12.7s, 29%, 1.07) and for one-handed exploration (symmetry: 9.8s, 21%, 1.60; repetition: 11.5s, 28%, 1.10) but not for two-handed exploration (symmetry: 14.4s, 30%, 1.26; repetition: 15.9s, 23%, 1.41). The interaction of objectness x exploration was not significant for RT [$F(2,45) = .50$, $p = .61$, partial $\eta^2 = .02$], or for errors [$F(2,45) = 2.86$, $p = .067$, partial $\eta^2 = .11$], but it was significant for sensitivity [$F(2,45) = 9.30$, $p < .001$, partial $\eta^2 =.29$]. Sensitivity was greater for one-object than for two-object stimuli for free exploration (d' of 1.88 versus 0.93) and for one-handed exploration (d' of 1.68 versus 1.10) but not for two-handed exploration (d' of 1.32 versus 1.34). Finally, the three-way interaction of regularity-type x objectness x exploration was not significant for RT [$\mathrm{F}(2,45) = .26$, $\mathrm{p} = .77$, partial $\eta2 = .012$], or for errors [$\mathrm{F}(2,45) = .21$, $\mathrm{p} = .81$, partial $\eta2 = .01$], or for sensitivity [$F(2,45) = 0.10$, $p = .90$, partial $\eta^2 =.00$], see Figure 10.

APPENDIX 4 - Results for Experiment 4

ANOVAs were conducted on RT and percentage of errors for regular trials and on sensitivity (d') for all trials. In the ANOVAs there were three within-subjects factors: regularity-type (symmetry or repetition), objectness (one-object or two-objects) and alignment (axis of regularity aligned with, or running across, the participant's body midline).

The main effects are reported first. Regularity-type was significant for RT [$F(1,31) = 90.67$, $p < .001$, partial $\eta^2 = .75$], errors [$F(1,31) = 52.01$, $p < .001$, partial $\eta^2 = .63$], and sensitivity [$F(1,31) = 78.27$, $p < .001$, partial $\eta^2 = .72$]. Consistent with previous research, and with Experiment 2, detection was easier for symmetry (0.82s, 3%, d' of 3.34) than repetition (1.21s, 12%, 2.52). Objectness was significant for RT [$F(1,31) = 51.97$, $p < .001$, partial $\eta^2 = .63$], errors [$F(1,31) = 48.56$, $p < .001$, partial $\eta^2 = .61$], and sensitivity [$F(1,31) = 7.84$, $p = .009$, partial $\eta^2 = .20$]. Detection was easier for two-objects (0.97s, 5%, d' of 3.00) than one-object (1.06s, 10%, 2.87) stimuli. Alignment was significant for RT [$F(1,31) = 9.42$, $p = .004$, partial $\eta^2 = .23$], and sensitivity [$F(1,31) = 7.19$, $p = .01$, partial $\eta^2 = .19$], but not for errors [$F(1,31) = 0.73$, $p = .40$, partial $\eta^2 = .02$]. Detection was faster and more sensitive for aligned (0.99s, 7%, d' of 3.00) compared to across (1.04s, 8%, 2.86) stimuli. Note that this result is the reverse of that obtained in Experiment 2, where across stimuli were detected faster, more accurately and more sensitively, than aligned stimuli. We propose that this difference occurred because frontoparallel rather than slanted views were presented here in Experiment 4.

Next, the interactions are reported. The interaction of regularity-type x objectness was significant for RT [$F(1,31) = 91.66$, $p < .001$, partial $\eta^2 = .75$], errors [$F(1,31) = 32.25$, $p < .001$, partial $\eta^2 = .51$], and sensitivity [$F(1,31) = 21.55$, $p < .001$, partial $\eta^2 = .41$]. Replicating Experiment 2, there was no significant difference in RT or errors in detecting symmetry for one-object (0.82s, 3%, d' of 3.41) compared to two-objects (0.83s, 3%, 3.28) stimuli, and there was a one-object advantage for sensitivity, whereas repetition was harder to detect for one-object (1.31s, 17%, 2.32) compared to two-objects (1.10s, 6%, 2.71) stimuli. The interaction of alignment x regularity-type was not significant for RT [$F(1,31) = 2.48$, $p = .125$, partial $\eta^2 = .07$], or errors [$F(1,31) = .40$, $p = .53$, partial $\eta^2 = .01$], but it was for sensitivity [$F(1,31) = 4.95$, $p = .03$, partial $\eta^2 = .14$]. The interaction of alignment x objectness was not significant for RT [$F(1,31) = 1.95$, $p = .18$, partial $\eta^2 = .06$], for errors [$F(1,31) = 2.14$, $p = .16$, partial $\eta^2 = .07$]) or for sensitivity [$F(1,31) = 1.87$, $p = .18$, partial $\eta^2 = .06$]. The three-way interaction of alignment x regularity-type x objectness was not significant for RT [$F(1,31) = .74$, $p = .40$, partial η^2 = .02], but it was for errors [$F(1,31) = 11.34$, $p = .002$, partial η^2 = .27], and for sensitivity [$F(1,31) = 8.39$, $p = .007$, partial η^2 = .21], see Figure 12.