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**The representation of shape:
understanding the role of symmetry in
haptic and visual inputs**

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by

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*"I've failed over and over and over again in my life.
And that is why I succeed."*

M. Jordan

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Abstract

Shape representation of an object can be achieved by vision but also by haptics. There are many potential cues which can influence the processes of shape representation. In this PhD thesis, I present seven studies that provide new insights about the way in which haptics and vision perceive some specific spatial properties (mainly regularities) with the final goal of assessing potential cues each modality uses in order to better understand the main cues involved in the process of shape representation. The first study (Part 1, Chapter 2) showed that externalising the haptic input into a visual sketch during haptic exploration improved the recognition of raised line drawings, possibly by reducing the working memory load. The following four chapters (Part 2, Chapters 3 - 6) represent the core of the thesis. They investigated detection of regularities such as mirror-reflection symmetry and repetition. Despite the ubiquitous occurrence of these regularities in our environment, repetition is a spatial property which has never been investigated by haptics before. Previous visual research suggested that symmetry could be a cue for the presence of one object whereas repetition could be a cue for the presence of multiple, similarly shaped, objects. Keeping this as the central interaction to compare the two modalities, I also manipulated several modality-specific factors, such as hand exploration for haptics and viewing perspective for vision (Chapter 3), line separation (Chapter 4), contour polarity (Chapter 5) and serial versus parallel exploration (Chapter 6). Together the results of these studies suggested that effects of regularities do not only reflect intrinsic properties of the world, but also reflect different, modality-specific ways in which shape information is collected. It is often taken for granted that we know what is and is not an object but defining objectness is not straightforward. I propose that the results of these studies can provide empirical evidence probing what it means to be an object for haptics versus for vision. The final part of the thesis reports two studies using symmetrical and asymmetrical 3D novel objects. In Chapter 7, I manipulated the position of objects and the orientation of their axes to investigate the spatial frames of reference used to represent objects haptically. Haptic detection of symmetry was better for objects presented in front of the body than those explored on the side. Finally, in Chapter 8 I used the same

3D stimuli in a preference task. Symmetry is usually associated with aesthetic preference in visual studies. Here the preference for symmetry was found for vision and, for the first time, for haptics. In summary, in several studies I compared visual and haptic perception to provide a novel way to assess which cues each modality uses to specify what is an object. Overall, I found several modality-specific differences in the detection of symmetry versus repetition. My results show that different cues are used to define objectness in vision and in touch and their effects on the two modalities are often not the same. My findings address and move a step forward toward the under-researched but key issue of what it means to be a perceptual object.

Chapter 1

1 Introduction and Chapters overview

This first chapter contains a short literature review about visual and haptic studies linked to regularity detection. This brief introduction will be enriched by broader and more specific introductions at the beginning of each experimental chapter. I discuss the main findings from the literature concerning the neural correlates of vision and haptics, and the commonalities and differences of their sensory processes, as well as discussing the processing strategies that these modalities use and their underlying representations. The chapters overview follows at the end of this chapter. This summarises the main hypotheses, paradigms and findings reported in each experimental chapter.

1.1 Introduction

The concept of shape representation is pervasive in the field of perception and cognition. Shapes representation underpins the more philosophical concept of an object. But what is an object? And what does it mean to perceive an object?

In vision there have been several attempts to try and define what an object is. But vision is not the only sensory modality that allows us to perceive and represent objects. Haptics is able to do this too. Haptics is our sense of active touch. Unlike vision, no one ever attempted to describe what an object is or what it means to perceive an object by haptics. But before trying to understand what an object is, it is crucial to understand how we perceive stimuli in the world, and how we represent their shapes.

Here I report a set of studies that focused on how stimuli can be explored by haptics and vision and how some specific spatial properties, such

as regularities like symmetry and repetition are perceived. This thesis aims to take a first step into uncovering the meaning of objectness for haptics. This, in turn, requires a deeper understanding of how shape is represented by haptics alone, and in relation to vision, in order to help us to build a more extensive and better defined concept of objectness.

Representation of shape and the concept of objectness

The concept of objectness is central to many aspects of spatial and conceptual organization in both perception and cognition. However, it has proven difficult to define what constitutes an object for vision (e.g., Feldman, 2003; Leek, Reppa & Arguin, 2005; Reppa, Greville & Leek, 2015) and this topic does not appear to have been addressed by haptics at all (Lawson, Ajvani & Cecchetto, in press). Researchers claiming to manipulate objectness often make little attempt to justify their choice of stimuli. This thesis aims to introduce an approach which allows us to identify and to compare potential cues to objectness in both vision and touch. This issue is important because it may, in turn, provide insights into what defines an object in vision and touch. The underlying idea is that objects are defined by some cues, which our perceptual system detects and uses to segregate the inputs from the chaotic information of the environment, into meaningful entities.

In this thesis, I manipulated a series of factors including modality (vision / haptics), regularity type (symmetry / repetition), contour separation (near / far), type of exploration (one / two handed for haptics; serial or simultaneous for vision), contour polarity (matched / mismatched) and spatial reference frame (aligned / across the axis of the body midline). The results of these studies provide converging evidence that allow us to distinguish between potential cues to objectness that are used by both vision and haptics (such as contour polarity and contour separation) and the cues which are modality-specific and, if so, whether that is because these cues can only influence one modality (such as number of hands used to explore a stimulus) or because the cues have differing influences on the two modalities (such as regularity type). I do not assume that objectness is an all or nothing property of a stimulus and I think that multiple cues combine to determine whether a given stimulus is perceived as an object.

I am not aware of any previous research that tries to define what it means to be a haptic object. My approach is, therefore, preliminary and I will not claim to provide conclusive evidence about the nature of objectness in haptics. Nevertheless, this topic is an important one which has been neglected for too long, and I think that progress can be made in trying to understand objectness across different modalities.

Symmetry as an important cue to objectness and shape representation

Mirror-reflection symmetry is a property of many natural and man-made objects and one of the most important perceptual features in the representation of shape (for reviews, see Treder, 2010; Tyler, 1995; Wagemans, 1995; 1997). Symmetry aids perceptual grouping and provides a cue for figure-ground segregation because elements which share symmetrical relations have a tendency to be aggregated together (Machilsen, Pauwels & Wagemans, 2009). There are other spatial regularities which are also studied in perception, such as repetition (translational symmetry) and rotation (rotational symmetry) however symmetry is usually the easiest to detect (Julesz, 1971).

It has been proposed that the presence of different types of regularity may be used to signal different properties in the world (Koning & Wagemans, 2009; Treder & van der Helm, 2007; van der Helm & Treder, 2009). Of particular relevance for the present thesis is the relation between regularities and objectness. Symmetry may signal the presence of a single, bilaterally symmetric object, whilst repetition signals the presence of multiple, similarly shaped objects (see Figure 1). This hypothesis has been supported by a number of studies which have reported an interaction between objectness and regularity-type (e.g., Baylis & Driver, 1995; Bertamini, Friedenberg & Kubovy, 1997; Bertamini, 2010; Koning & Wagemans, 2009; Lawson & Cecchetto, 2015). These authors found that symmetry was easier to detect for one-object stimuli with two regular sides than for two-objects stimuli where the facing sides of the two objects were regular. In contrast, repetition was easier to detect for two-objects stimuli than one-object stimuli.

A final point about the terminology used in this thesis must be made. In everyday language, symmetry is usually understood to refer only to bilateral mirror-reflective symmetry. However, in the scientific literature the

term symmetry has often been used to also encompass other regularities such as the repetition of a structure by a translation (translational symmetry). There has been a strong consensus to use symmetry and repetition by the researchers investigating visual regularity detection, for example, by Baylis and Driver (1991, 1994, 1995), Chen and Sio (2015), Koning and Wagemans (2009), Farell (2015), Treder and van der Helm (2007), van der Helm and Treder (2009), and van der Vloed, Csathó & van der Helm (2005). For reasons of consistency, I have used the terms *symmetry* and *repetition* also for my haptic regularity detection tasks throughout the whole thesis.

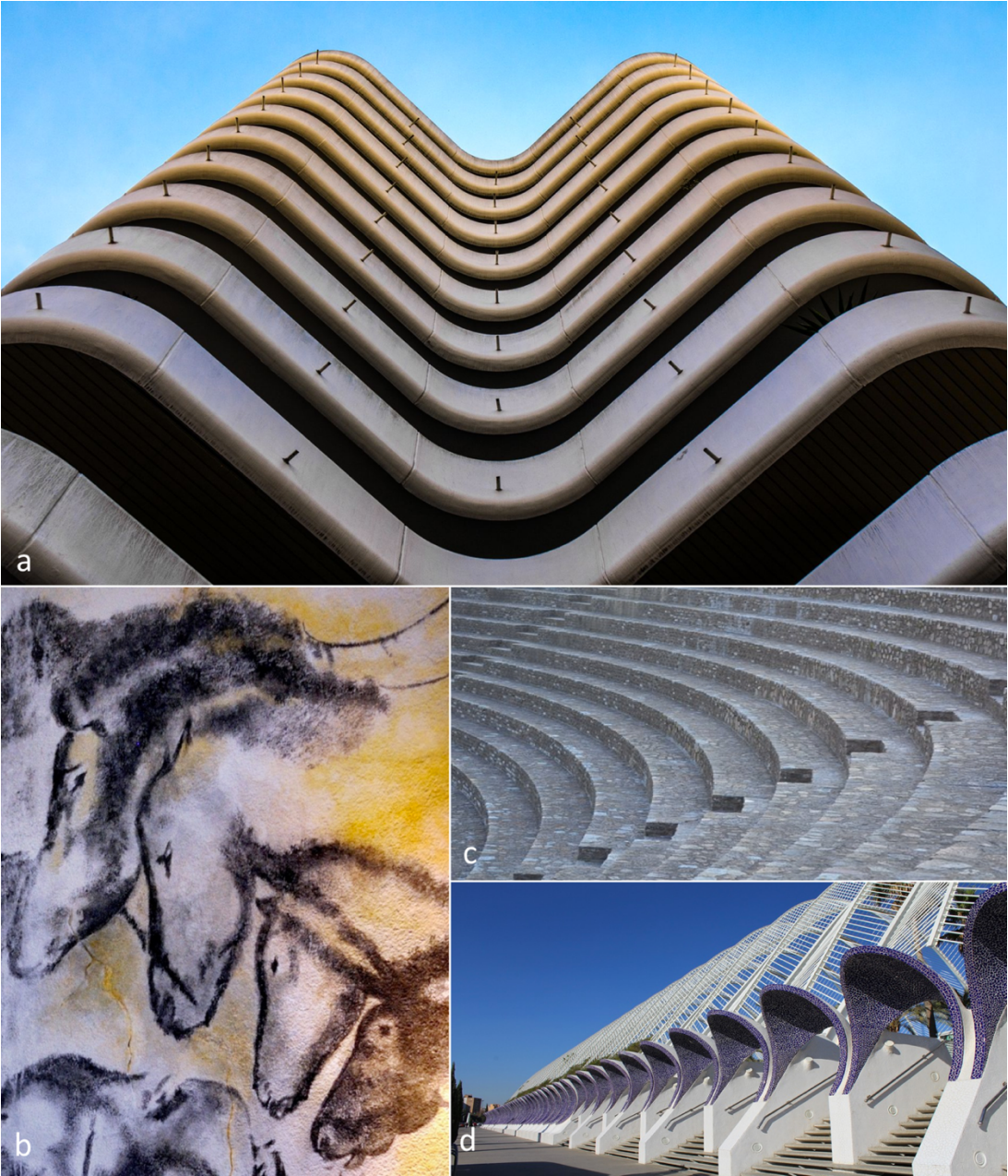


Figure 1. a) A symmetrical building. <https://unsplash.com/photos/bEbwgH6wP6Y> Photo by Valentin Gautier, Mariadeck, Bordeaux, France. b) An illustration of

repetition as a cue to the presence of multiple, similarly shaped objects. Prehistoric art from Chauvet-Pont-d'Arc Cave (https://en.wikipedia.org/wiki/Chauvet_Cave). The four repeated contours of horse heads occur because the artist depicted a herd of animals with similar shapes and orientations. Image by T. Thoams, <https://www.flickr.com/photos/theadventurouseye/5602930382/> licensed under <https://creativecommons.org/licenses/by-sa/2.0/>. c) Repeated stairs of an amphitheatre in Lyon (<https://pixabay.com/it/anfiteatro-lione-costruzione-1004396/>). d) A symmetrical and repeated building in Valencia (<https://pixabay.com/it/valencia-spagna-notte-riflesso-960178/>).

Symmetry perception by vision

Royer (1981) suggested that symmetry is the most salient global organizational aspect of visual shapes. The advantage in detecting bilateral symmetric patterns (especially those symmetrical along the vertical axis) is found not only with adults, but already in infancy (Boswell, 1976; Gaines, 1969; Pashler, 1990; Wagemans, 1997; Wenderoth, 1994). Even fourth month old babies can judge symmetry (e.g., Bornstein & Krinsky, 1985).

Symmetry is one of the major grouping principles for the representation of visual shapes (e.g., 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, et al., 2009), amodal completion (Kanizsa, 1985; van Lier, van der Helm & Leeuwenberg, 1995) and object recognition (Pashler, 1990; Vetter & Poggio, 1994). Symmetry has been shown to be a crucial factor in the recognition processes of 2D shapes (e.g., Giaquinto, 2005; Marr & Nishihara, 1978) and 3D objects (Large, McMullen & Hamm, 2003; Liu & Kersten, 2003; Sekuler & Swimmer, 2000; Vetter & Poggio, 1994). Even from an evolutionary point of view, the importance of symmetry has been well documented; symmetrical relations between body parts seem to reflect a sign for genetic quality in mate selection and reproduction (e.g. Grammer, Fink, Møller & Thornhill, 2003).

The processes that give rise to the perceptual salience of symmetry are not well known. Being able to detect symmetry without being instructed is

consistent with the assumption that symmetry is part of the spatial organizational structure of visual shape perception (Royer, 1981). Detection of symmetry can be extremely quick (within a few tens of milliseconds) and not mediated by a conscious cognitive effort (for a review see, Treder, 2010; Tyler, 1995; Wagemans, 1995, 1997) especially when symmetry is organized along a vertical axis (e.g. Wenderoth, 1994).

The most salient condition for symmetry to be detected occurs when it contains a vertical axis (which I will also refer to as symmetry *along* the body midline); symmetrical elements organized along a horizontal axis (which I will refer to as *across* the body midline) are less perceptually salient but when the axis orientation is oblique, the perceptual strength of symmetry is even lower (Wenderoth, 1994). This perceptual scale might be the result of visual experience adapting to process the structure of the visual world where natural and artificial objects are often vertically symmetrical (for example, human and animal bodies and faces, flowers, buildings). Studies from patients born without the corpus callosum suggested that the bilateral symmetrical organization of the visual system itself might be one of the reasons for the higher perceptual salience of symmetry along the vertical axis (Herbert & Humphrey, 1996).

It has been claimed that salience of symmetry might be the result of the need to recognize objects regardless of their position and orientation in the visual field (Enquist & Arak, 1994). Indeed, it has been proved that symmetry facilitates figure/ground segregation (Palmer, 1991) and it is very important in computational models of object representation and recognition (Biederman, 1987).

The idea that regularities such as symmetry and repetition could be potential cues to objectness has been investigated before. In particular, Baylis and Driver (1995) and Bertamini et al. (1997; see also FriedenberG & Bertamini, 2000) investigated whether symmetry could be a cue for the presence of one object and repetition a cue for the presence of multiple objects. In both studies they used regularity detection tasks and it was found that 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, suggesting the role of some mental matching strategies.

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 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 multiple, similarly shaped objects, so it may be easier to detect for two-objects stimuli. Using slanted versions of previous stimuli used by Baylis and Driver (1995) and Bertamini et al. (1997), Koning and Wagemans (2009) replicated the interaction of regularity-type by objectness. They therefore concluded that it was caused by structural coding of the stimuli, rather than by the choice of cognitive matching strategies¹.

One way to 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. Vision is not the only sensory modality that allows us to explore objects in the world. Many objects and many objects' properties can also be efficiently perceived by haptics, our sense of active touch.

Symmetry perception by haptics

Compared to vision, there have been relatively few studies on the effects of symmetry in haptics (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;

Simmons & Locher, 1979). Even the pioneer of haptics studies Katz (1925/1989) neglected the haptic perception of symmetry in his work. Surprisingly, studies on detection of haptic repetition have never been reported in literature.

The haptic perceptual system encodes information from cutaneous and kinaesthetic receptors (Loomis & Lederman, 1986) and like vision it can be very accurate in perceptual recognition of familiar objects (Klatzky, Lederman & Metzger, 1985; Lawson & Bracken, 2011) and in the detection of salient attributes of the spatial layout of tangible displays such as object shape, size and orientation (Lawson, 2009; Kappers, 2013) and their bilateral symmetry (e.g., Ballesteros, Manga & Reales, 1997; Ballesteros et al., 1998; Ballesteros & Reales, 2004).

However, the haptic perceptual system must pursue a sequential exploration of a stimulus rather than a parallel processing of it (as usually occurs for vision), so it is possible that symmetry detection may follow other grouping mechanisms in haptics. Diversity in the relative area that can be scanned at once, diversity in timing, and separation of the cortical pathways between haptics and vision are all factors that likely contribute to symmetry being less salient to haptics than to vision (Cattaneo et al., 2014). A brief review of the most important studies concerning haptic symmetry perception and related to this thesis will follow below.

Millar (1978) conducted the first experiment on haptics and symmetry, in which she used pair of matching and not matching Braille configurations. The author manipulated the presence of symmetry and numerosity in configurations of the raised dots. Here results showed that numerosity, rather than the presence of symmetry affected the performance suggesting that texture properties rather than shape are more haptically salient for these kinds of stimuli. Millar suggested that, in the absence of spatial reference, it was easier to code differences in texture rather than difference in spatial organization of shape. Properties such textures and hardness are more salient than spatial information such as form and size for haptics (Klatzky, Lederman & Reed, 1987).

Locker and Simmons (1978) used symmetrical and asymmetrical planar polygons varying in complexity and they found that detection was faster and more accurate for asymmetrical objects rather than symmetrical ones. In their

study errors for identifying for symmetrical shapes were higher (12%) than for asymmetrical shapes (3%).

Ballesteros et al. (1997) investigated the accuracy of haptic symmetry detection in 2D raised line stimuli and 3D objects. They manipulated several factors such as objects dimensionality, exploration and presentation time. Their task was explicit symmetry detection using one finger from one hand or using two fingers from two hands. For haptics it was easier to perceive 3D objects than 2D raised lines. The authors explained these results by suggesting that 3D objects offered more informative exploration (enclosing exploratory procedures rather than just contour following) which increased the availability of reference information, thus improving symmetry detection. Also Ballesteros et al. (1997) showed that asymmetrical objects were assessed more accurately (81% were correctly designated as asymmetrical) than symmetrical ones (60%).

Ballesteros et al. (1998) used an implicit task in which half the stimuli were closed shapes and half were open. The task was to haptically explore these stimuli and detect whether the shape was open or closed, with half the stimuli symmetrical and half irregular in both cases. The authors reported that when reference information for spatial coding was provided, symmetry could be encoded from shapes, as usually occurs for vision, even during an implicit task. The presence of symmetry improved performance on the spatial task, similar to the incidental coding of symmetry which has been found to occur for vision (Wagemans, 1995). This suggested that symmetry could be processed even in very early stages of the haptic exploration (Ballesteros et al., 1998).

Ballesteros et al. (2004) manipulated the depth of the stimuli, while keeping shape, size and complexity constant in a symmetry detection task. They compared explicit haptic symmetry detection for raised line, raised surface, 3D short objects and 3D tall objects. Increasing the height of the stimuli improved participants' haptic performance with symmetrical stimuli; supporting the reference hypothesis (Millar, 1994). However, the stimuli axis orientation was not manipulated, leaving unclear whether this bimanual alignment advantage was caused by the nature of exploration (using one versus two handed) or by matching the axis of symmetry of exploration to the axis of symmetry of the stimulus (since all stimuli were aligned with the body

midline). In addition, none of these studies by Ballesteros and colleagues manipulated the position of the object in relation to the body of the participants; stimuli were always presented directly in front position of the participant.

In a series of more recent studies, Cattaneo and colleagues (2010, 2013) extended research on blind participants, focusing on whether the presence of symmetry could facilitate memorization of haptic patterns. They presented a short memory task in which participants were required to haptically explore, memorize and retrieve 2D haptic matrix configurations. They also manipulated the axis of symmetry (aligned or across the body midline). Early and late blind participants showed better memory performance, which the authors interpreted as an effect of symmetry in easing the storage of partial information. Interestingly, early blind participants were also immune to the effect of axis orientation, whereas sighted and late blind participants showed better performances recalling symmetrical patterns if the axis was aligned to their body midline. The authors suggested that this finding might explain the vertical (aligned to the body midline) symmetry advantage consistently reported in literature, which appear to originate from previous visual experience of the world.

In summary, symmetry detection by haptics seems to be favoured by a bimanual exploration of the object which is aligned in front of the observer's body midline (e.g., Ballesteros et al., 1998). For stimuli aligned with the body midline, symmetry detection may be privileged because the axis of symmetry of the stimuli is coincident with the 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 et al., 1998; Ballesteros & Reales, 2004). The advantage offered by this position and alignment has been supported by several haptic studies (Ballesteros et al., 1997; Ballesteros et al., 1998; Ballesteros & Reales, 2004; Cecchetto & Lawson, in press; Lawson et al., in press; Locher & Simmons, 1978; Millar, 1978, 1994). This positioning would provide an effective reference frame (Millar, 1994) about which the acquired spatial information can be structured. Consequently, it can be assumed that any effect of symmetry depends on the availability of spatial reference information.

Overall, these studies suggest that symmetry could be detected haptically in both 2D and 3D objects, but that symmetry is less salient for haptics than for vision (see Cattaneo et al., 2014). From the results reported above, several factors seem to emerge which can modulate the saliency of symmetry for haptics including material properties (such as texture), pattern complexity, size, dimensionality (2D/3D) and exploratory strategy. Finally, concerning the role of exploratory strategies, haptic symmetry detection seems to benefit from a two handed exploration aligned to the body midline (e.g., Ballesteros et al., 1998).

Neural correlates of symmetry for vision and haptics

An in depth review about the neural correlates of visual and haptic symmetry detection is beyond the scope of this thesis therefore only the main findings will be reported here. Sasaki, Vanduffel, Knutsen, Tyler and Tootell (2005) used functional magnetic resonance imaging (fMRI) while participants had to visually discriminate symmetrical from random stimuli on a vertical, horizontal and oblique axis. Detection of symmetry was associated with activation of high-order visual areas (such as V3, V4, V5/MT, V7) and the lateral occipital complex (LOC). Early visual areas (V1 and V2) were barely activated. The authors also reported a stronger activation for vertical, rather than horizontal, symmetry in agreement with the higher perceptual salience for body aligned symmetry. Considering that symmetry is a critical cue in shape and object detection (Machilsen et al., 2009), it has been suggested that activation of LOC might depend on the role of this region in object recognition processes (e.g. Ales, Appelbaum, Cottureau & Norcia, 2013; Grill-Spector, Kourtzi & Kanwisher, 2001). Nevertheless, Sasaki et al. (2005) showed that LOC areas were actually activated primarily by symmetry and not by general object-like components presented in their stimuli.

Consistent with this fMRI evidence, electrophysiological (ERP) studies agree that visual symmetry is, for the most part, mediated by extrastriate visual activity and not by the primary visual cortex as suggested by the presence of a sustained posterior negativity (SPN) component (e.g. Makin, Wilton, Pecchinenda & Bertamini, 2012; Makin, Rampone, Pecchinenda &

Bertamini, 2013) and the lack of symmetry responses in early components (P1). Targeting these extrastriate regions using transcranial magnetic stimulation (TMS) other authors have confirmed the causal role of the LOC in detecting visual symmetry (e.g., Bona, Herbert, Toneatto, Silvanto & Cattaneo, 2014; Cattaneo, Mattavelli, Papagno, Herbert & Silvanto, 2011).

Research on neural correlates of symmetry has recently been extended to the haptic modality. In the fMRI study of Bauer, Yazzolino, Hirsch, Cattaneo, Vecchi and Merabet (2014) participants (who were either early blind or blindfolded sighted) had to discriminate between symmetrical and random tactile configurations. The authors reported that similar areas were activated in both groups during haptic and visual detection of symmetry (despite the lack of previous visual experience for the early blind individuals). In particular LOC appeared to be crucial in mediating haptic symmetry detection. Critically, an activation of early visual cortex was observed in the early blind group, suggesting crossmodal cortical plasticity.

Processing strategies and underlying representation in vision and haptics

To successfully use our hands to grasp and handle an object, our brain needs information about its size, shape and mass. These kinds of information are usually provided by vision and haptics. Vision perception relies solely on information derived from the retina whereas haptics is based on information integrated from proprioceptive, tactile and pressure cues across time (Gibson, 1966). While exploring and manipulating an object with our hands, usually both haptic and visual information are accessible to the perceptual system. Theoretically, the combination of both streams of information into a single percept would require a shared integration process.

Converging evidence from imaging studies shows that vision and haptics share resources. In particular, Amedi, Malach, Hendler, Peled, and Zohary (2001) showed that both haptic and visual object exploration activate the LOC which is the region involved in visual object recognition (Grill-Spector et al., 2001) and specifically in the processing of visual shape (Kourtzi, Erb, Grodd, & Bühlhoff, 2003; Zhang, Weisser, Stilla, Prather, & Sathian, 2004). In control studies, the LOC has been found to not be activated by auditory

stimuli which cued object identity, such as the sound of an engine (Amedi, Jacobson, Hendler, Malach, & Zohary, 2002). If both the haptic and visual perceptual systems activate the LOC region for shape processing (and the LOctv, see Amedi et al., 2002) then the two sensory modalities might use the same representation of shape for object recognition.

Commonalities and differences across vision and haptics

Similarly for vision and haptics, their spatial resolution is not homogeneous across their receptive surfaces. For example, vision acuity is greatest on the fovea (1 minute of arc), where retinal ganglion cells have the smallest receptive fields compared to those in the visual periphery, which have the largest receptive fields. For haptics, the fingertips have the highest spatial resolution reflecting the high innervation density and the small receptive fields whereas in other regions, like the calf or the thigh, receptive fields of somatosensory neurons are large and with low spatial resolution. The two-points discrimination threshold, which is the minimum distance required to distinguish two objects, is about 2-3mm at the fingertips (Lederman, 1991) and about 40mm on the thigh.

Despite the common ability to extract many of the same spatial information from an object, there are fundamental differences in the way in which vision and haptic modalities extract these features. First of all, the dimensionality of the input information is radically different: vision operates on 2D retinal inputs whereas haptics operates on 3D space (Cooke, Wallraven & Bühlhoff, 2007).

Many differences between the two modalities concern spatial scale and sampling properties. Vision is efficient in large spaces and can function simultaneously at several scale, whereas haptic can only operate in near-body spaces and it can be affected by the scale of the feature that it is perceiving (e.g. curvature perception, see Klatzky & Lederman, 2003).

In the fovea,

Despite the ability of both vision and haptics to extract geometric properties and their spatial properties, 'global' spatial processing is generally considered to be easier for the visual system, while the haptic system is largely

limited to the extraction of 'local' spatial relationships (Klatzky & Lederman, 2003).

Furthermore, extraction of visual features requires processing at higher levels, beyond the retina, whereas haptics is able to extract some information (for example, pressure or temperature) at the most peripheral level of receptors (skin, tongue). Finally, it is commonly accepted that object shape and other global properties (e.g. symmetry, see Baylis & Driver, 1995) can be processed in parallel by the visual system (especially if a stimulus falls fully within the foveal area and so does not require any saccades to be fully explored) whereas these features must usually be sampled in a serial manner by haptics, due to the much more limited field of view (Loomis, Klatzky & Lederman, 1991).

An interesting question would be to understand how such preferences for scales and features affect the final object representation and behaviour for visual versus haptic inputs. A way to start and answering this question might come from the manipulation of potential spatial cues belonging to stimuli explored by both modalities. A similar idea was behind the purpose of the current thesis.

Symmetry and preference in vision and haptics

Symmetry has also been associated with aesthetic preference. Many authors have argued for a robust connection between symmetry and beauty. In 1952, for example the physicist and mathematician Hermann Weyl wrote, "Beauty is bound up with symmetry" (p. 3). Ramachandran and Hirstein (1999) defined symmetry as one of the key principles of the aesthetic experience.

Many studies reported that visual symmetry is a powerful predictor of preference (Eisenman, 1967; Eisenman & Gellens, 1968; Jacobsen & Höfel, 2001, 2002; Jacobsen, Schubotz, Höfel & van Cramon, 2006; Tinio & Leder, 2009) as well as for implicit preference (e.g. Makin, Pecchinenda & Bertamini, 2012). One reason could be that symmetry is an important indicator of good, practical and effective design (McManus, 2005). The preference for symmetry occurs at a very early stage. By 4 to 5 months from birth, babies can show a

preference for symmetrical patterns (Humphrey & Humphrey, 1989). Symmetrical physical characteristics of a human being is perceived as an indicator of a stable and positive development (Thornhill & Gangestad, 1999). From an evolutionary perspective, symmetrical faces are thought to be preferred as this is considered a sign of health and good genes and so it is used to assist in the selection of a potential partner for successful reproduction (Grammer & Thornhill, 1994; Jones, Little, Tiddeman, Burt & Perrett, 2001).

The aesthetic preference for symmetry may arise from symmetrical stimuli being easier to process, perhaps because they convey less information than asymmetrical ones (Garner, 1974). This is consistent with the perceptual fluency hypothesis which states that the positive aesthetic experience depends on the ease with which an object can be processed (Reber, Wurtz, & Zimmermann, 2004).

Despite the undoubted importance that aesthetic attributes of touch have on our quality of life, there is surprisingly little empirical research on this topic (Essick, McGlone, Dancer, Fabricant, Ragin, Phillips, Jones & Guest, 2010). Moreover, most extant research has investigated passive, tactile stimulation (e.g., McGlone, Wessberg & Olausson, 2014) rather than aesthetic responses to active, haptic inputs (Carbon & Jakesch, 2013). For example, Ekman, Hosman and Lindstrom (1965) reported preferences were proportional to the softness of various sandpapers, cardboards, and papers, whilst Hilsenrat and Reiner (2011) showed that softer and smoother surfaces were preferred, whilst Jakesch and Carbon (2011) reported a preference for rounded objects. Also the ability to handle objects can positively influence attitudes towards the object (Grohmann, Spangenberg & Sprott, 2007; Peck & Childers, 2003a, 2003b).

As far as I am aware, only one study has investigated whether haptics shows a preference for symmetry. Schmalzer (2014) examined whether judgments of pleasantness and interestingness varied across three levels of symmetry (perfect, partial and random). The author used 2D planar wooden triangles glued onto cardboard and did not manipulate stimulus alignment. Perfectly symmetrical triangles were preferred over partially symmetric and asymmetric triangles, consistent with the findings reported by Gartus and Leder (2013) in their similarly designed visual study, and suggesting an influence of symmetry on haptic aesthetics.

To conclude this literature review I would like to highlight some of the main issues which I tried to investigate.

- First, is it possible to improve touch recognition of raised line drawings by allowing visual feedback of haptically acquired information? Would allowing participants to sketch what they feel and to see the sketch during haptic exploration decrease the working memory overload and hence improve shape representation and finally the recognition of objects?

- Second, compared to vision, how does haptics perceive symmetry and repetition during shape exploration? And what is the role of objectness in regularity detection for vision and touch? Can factors be manipulated in order to infer which cues are used to define objectness?

- Third, can regularities be detected when participants cannot rely on their body midline to provide a reference frame? And, if so, how does this differ from regularity detection for stimuli with the axis of regularity aligned with their body midline?

- And finally, given that symmetry is associated with aesthetic preference for vision, is there a similar effect for haptics?

In the next section, I briefly introduce how these questions were investigated in the corresponding chapters. A critical section discussing the limitations will follow, which will cover some suggestions and ideas for future research.

1.2 Chapters overview

Aiming to investigate how haptics and vision represent shapes, I addressed several questions and used several kinds of stimuli and experimental paradigms. For simplicity, this PhD thesis has been divided in three parts depending on the stimuli used and on the kind of tasks employed. Each part used different stimuli (2D, 3D; novel, familiar) and addressed different questions. As suggested by Lawson and Bracken (2011) haptic stimuli can provide different spatial information dependent on the amount of depth that they can provide. The order in which I divided this thesis reflects the increasing amount of depth information of the stimuli and partially the kinds of paradigms that I used in each study. Chapters did not necessarily follow one to the next one but they were all related in the common attempt to understand shape representation by haptics and vision. In Part 1, I used raised line stimuli to test the role of memory load in a shape recognition task. In Part 2, I used filled planar shapes and also raised lines to probe cues to objectness using regularity detection tasks by vision and haptics. Finally, in Part 3 I used 3D novel objects to test the role of reference frames in a symmetry detection task and presence of symmetry/minor asymmetries in a preference task.

Part 1 – Shape representation and object recognition using raised line drawings

In the investigation of shape representation, the most obvious task to start the study on this topic must be shape recognition. *Chapter 2*, described a haptic experiment using raised line drawings (thermoform and plastic lines) and an object recognition task. Here, I focused on the serial nature of haptic exploration and on its effects on the representation of shape. In this study, 2D shapes of common objects had to be explored by haptics, represented and recognised. These stimuli are widely used in several haptic contexts but they are also very hard to identify by touch, which makes them ideal stimuli to study how basic shape information is acquired and eventually recognized. In this first study, I tested a solution to improve the recognition of these objects using a simultaneous externalization of the object, based on a real time conversion of the haptic input into a visual input.

One of the most unique features of haptic perception is the serial nature of spatial information acquisition. Compared to vision, haptics needs to explore the objects of the world serializing and integrating haptic information into meaningful shapes.

To better understand how haptics acquires information from these stimuli I designed an experiment which offered a real time visual feedback of the haptic stimulus being felt. I wanted to investigate whether a major component of the difficulty was haptically acquiring, integrating and maintaining shape information in the working memory.

Wijntjes, van Lienen, Verstijnen and Kappers (2008b) and Kalia and Sinha (2011) reported that drawings which participants had failed to identify by touch alone could often subsequently be named if they were externalised through a sketch. However, from these studies it was not clear whether the main difficulty in naming these stimuli derived from the laboriousness of holding the spatial information in working memory or from problems in connecting that information to stored visual representations. I extended this task and found that sketching whilst touching improved drawing identification even more than sketching after touching, but only if people could see their sketches. The results suggested that simultaneous sketching aided identification possibly by reducing the burden on the working memory and helping to guide haptic exploration.

Part 2 – Shape representation and potential cues to objectness: role of symmetry and repetition

In four chapters, I compared regularity detection by haptics and by vision with the overarching aim of investigating multiple cues to objectness for vision and touch.

In *Chapter 3*, I reported an experiment designed to investigate shape perception across vision and haptics manipulating the presence or absence of two spatial regularities, symmetry and repetition. Koning and Wagemans (2009) found an interaction between objectness and regularity-type, replicating previous results (Baylis & Driver, 1995; Bertamini et al., 1997). They therefore concluded that structural differences between stimuli, and not the

use of high-level matching strategies, underlay the one-object advantage for symmetry and the two-objects advantage for repetition.

In four experiments, I tested whether Koning and Wagemans' (2009) conclusion generalised to regularity detection of symmetry and repetition in a different modality, haptics (our sense of active touch). Haptics is the only other modality besides vision which is specialised in extracting shape information and there are many similarities in how vision and touch identify objects. It is well established that haptics can detect symmetry (Cattaneo et al., 2014, for a recent review) but, as far as I am aware, no one has ever focused on haptic detection of repetition. Extending the research to both regularities and using haptic 2D flat stimuli, similar to the visual ones used by Koning and Wagemans, allowed us to investigate whether the typical interaction between regularity and objectness would also occur for haptics. The main reason to run this study was to understand whether potential spatial cues to objectness would produce the same effects across the two modalities leading to the same perception of objectness.

The results showed an important difference between visual and haptic regularity detection. For vision, I found a one-object advantage for detecting symmetry and a two-objects advantage for detecting repetition. This replicated the interaction reported by Koning and Wagemans (2009) and others. However, for haptics, there was a one-object advantage for both symmetry and repetition detection. These results suggested that effects on regularity detection may not be informing us about properties of the external world. Instead they may be telling us about differences in processing across our sensory systems.

A limitation of this study comes from the work of van der Helm and Treder (2009) in which the authors argued about drawing conclusions from detection of regularity (one and two-object symmetrical with matched contour polarities) to anti-regularity (one and two-objects repeated with unmatched contour polarities). In the following chapters, I tried to overcome this issue using line (contour) stimuli at different separations (Chapter 4) and matching contour polarity of the stimuli (Chapter 5). In the last study included in Part 2 (Chapter 6) I manipulated visual presentation to match the haptic presentation in order to make vision exploration and perception more similar to that of haptics.

In *Chapter 4*, I ran a new study based on the prediction that closer contours are more likely to be perceived as belonging to the same object and more distant contours as belonging to two different objects (see also Corballis & Roldan, 1974; Treder & van der Helm, 2007). With this hypothesis, I predicted that it should be easier to detect symmetry when contours are closer because both cues (contour separation and the type of regularity) should indicate that one object is present. On the other hand, repetition should be more difficult to detect when two contours are closer because one cue (contour separation) indicates that one object is present whereas the other cue (the type of regularity occurring - here, repetition) indicates that multiple objects are present. I investigated these predictions in three experiments, testing whether effects of the type of regularity being detected (symmetry versus repetition) interacted with contour separation. My approach was conceptually similar to that designed by Treder and van der Helm (2007) in which they varied regularity-type (symmetry versus repetition) and stereoscopic depth (the two stimulus halves were on the same versus on different depth planes) to investigate how regularity detection was influenced by these cues which provided consistent or conflicting interpretations of objectness. To avoid the issues raised by van der Helm and Treder (2009), concerning the misinterpretation of true-regularities and anti-regularities the experiments in this study presented just contour lines rather than planar shapes.

The results from Chapter 4 with contour-only stimuli were consistent with those reported in previous Chapter 3. The predicted objectness by regularity interaction was found for vision but not for haptics. Thus, for vision, but not for haptics, these results were consistent with small contour separations and symmetry providing consistent cues that a single object was present whilst large contour separations and repetition provided consistent cues that two objects were present.

One of the advantages of Chapter 4 compared to Chapter 3 was that using just contours rather than flat objects overcame the issue raised by Treder and van der Helm (2007) about regularities and anti-regularities. On the other hand, the advantage of Chapter 3 compared to Chapter 4 was the use of filled planar shapes as stimuli for which figure-ground assignment was clear-cut whereas, arguably, the line-only stimuli used in Chapter 4 might not have been interpreted as objects at all. A limitation of the studies reported in

Chapter 3 was a mismatch between contour polarity and regularity. In particular, my previous symmetrical stimuli (1object-outer-sides and 2objects-inner-sides) had contours with matched concavities and convexities whereas my repeated stimuli (1object-outer-sides and 2objects-inner-sides) had contours with opposite concavities and convexities.

In *Chapter 5*, I aimed to merge the designs of Chapter 3 and Chapter 4 to combine the strengths of both approaches. Here, I introduced a new objectness condition (2objects-right-sides). This provided a mismatching polarity condition for symmetry (anti-symmetry) and a matched polarity condition for repetition (true-repetition). In two experiments, the role of contour polarity was investigated in regularity detection by haptics (Experiment 1) and vision (Experiment 2). The same one-object (1object-outer-sides) and two-objects (2objects-inner-sides and 2objects-right-sides) stimuli were used for true-repetition, anti-repetition, true symmetry and anti-symmetry detection.

Once again, the results revealed a clear difference between haptic and visual detection of regularities. For haptics, performance deteriorated strikingly when concavities and convexities mismatched, for anti-repetition and anti-symmetry two-object stimuli. A different pattern of performance was obtained for vision which seemed more affected by whether one versus two objects were presented rather than by a match in contour polarity. Thus, surprisingly, the results suggested that repetition detection differs in its sensitivity to contour polarity (regularity versus anti-regularity) and to objectness (with the two critical contours belonging to one versus two objects) for haptics and vision. The results suggested that for regularity detection, contour polarity may, surprisingly, be more important for haptics than for vision.

In the final chapter of this part, *Chapter 6*, I investigated whether differences between haptic and vision in previous studies could depend on the way objects were presented and explored. In previous research, I found differences in regularity detection between vision and haptics (Cecchetto & Lawson, in press). In the present study I hypothesized that one reason for this modality-specific difference could be the different ways in which vision and haptics explore and acquire information. Under normal circumstances, vision can rely on fast and parallel processing of a stimulus whereas haptics typically

requires slower and serial exploration of it. Thus, in the present study I investigated the effects of visual presentation, forcing the vision modality to perceive the world more like the haptic modality. In the first experiment, I forced vision to explore stimuli serially, using a movable aperture. This paradigm allowed us to restrict the field of view so that only a small area of the stimulus could be seen at a given time and place. As a consequence, this method allowed us to re-examine the effect of manipulating objectness on symmetry compared to repetition detection. Consistent with my predictions, the results showed that serialising visual presentation, by using an aperture, eliminated the interaction between objectness and regularity, hence making visual regularity detection more similar to that of haptics.

In the second experiment, I used the same paradigm to provide empirical evidence to support the claim of Baylis and Driver (1994, 2001) that symmetry could be detected simultaneously whereas repetition had to rely on a serial exploration of each vertex of the stimulus. The results showed no cost of complexity for symmetry detection but a cost for repetition during a normal, simultaneous observation. In contrast using a serial exploration, no effects of complexity were found.

In the third and final experiment, I studied whether regularity detection was affected by the duration of the simultaneous presentation. Regardless of presentation duration, repetition detection was always disrupted by increased complexity. In contrast, symmetry detection showed no significant cost of increasing complexity for unlimited duration presentations and a weaker cost of complexity compared to repetition detection for stimuli presented briefly.

Overall when stimuli were presented simultaneously, the results showed a greater cost of complexity for repetition detection than symmetry detection (replicating Baylis & Driver, 1994, 2001). In contrast, when stimuli were explored serially, complexity had no influence on regularity detection for either symmetry detection or repetition detection. These results support the claim that effects on regularity detection reflect how stimulus information is acquired by a given modality, rather than reflecting necessary properties of that modality.

Part 3 – Symmetry detection and preference judgment using 3D novel objects

The last part of the thesis includes two chapters in which I used 3D novel objects in a symmetry detection task (Chapter 7) and in a preference task (Chapter 8). For haptic tasks, 3D (rather than 2D) objects are optimal stimuli because they provide useful depth information and allow multiple exploratory procedures. Depth has been shown to play a crucial role in object recognition (e.g., Lawson & Bracken, 2011) and symmetry detection (e.g., Ballesteros et al., 1997; 2004) with 3D objects encoded more effectively than 2D objects by haptics.

In *Chapter 7*, I investigated the role of reference frames in an explicit symmetry perception task by haptics. According to the reference frame hypothesis, bimanual exploration allows participants to relate the position of their hands to their own body midline. This provides an effective spatial reference for coding the presence of symmetry in external objects (Millar, 1994).

What was still not clear was whether this advantage relied on the position of the objects relative to the body or on the orientation of their axis of symmetry, which was also aligned to their body. The aim of the first experiment was to disentangle whether the reference frame was hand-centred or body-centred. To answer this question, I examined the role of reference frame by forcing a two handed exploration and by varying object position (front or right-side of the participant) and orientation of the axis of symmetry (aligned or across the participant's body midline) of 3D novel objects. If participants used a body-centred reference frame I would expect a main effect of position, with symmetrical objects presented in front being better explored than those presented on the right side. On the other hand, if participants used a hand-centred reference frames then I would expect to find no difference between the two axis orientations, suggesting that hands could adjust their positions to better fit the orientation of the objects.

The results showed that only when objects were both placed in front and with their axis aligned to the body midline could the body-centred reference frame be used efficiently. This result was in contrast to the findings of Kappers (2007) who argued in favour of a hand-centred reference frame as the most important egocentric reference frame (although note that here the

haptic task was different). This difference suggests that, generally, the reference frame used to encode spatial relations may differ across tasks and that, specifically, for symmetry detection, a combination of the body and the hand reference frames might be more efficient.

The last study reported in this thesis, in *Chapter 8*, describes a haptic and visual preference task. As previously mentioned, symmetry can be detected quickly and effectively by vision, and generally symmetry has an implicit effect on visual preference, even when judging meaningless abstract stimuli (Makin et al., 2012). Given the ability of haptics to detect symmetry, I hypothesized that, providing the right conditions, symmetry might also play an influence in judgments of haptic preference. To test this hypothesis, I created pairs of 3D novel objects which were explored in a pairwise preference task. Objects from each pair were composed of the same parts but arranged differently, such that one was always symmetrical and the other was always partially asymmetrical. Furthermore, I manipulated the object's axis orientation (aligned or across the participant's body midline), to try to affect the overall perceptual fluency of symmetry detection. I expected symmetry to be more salient for both haptic and visual exploration when the objects were presented with their axis of symmetry aligned to the body midline. With this orientation, a bimanual exploration or a quick look should allow symmetry to be detected easily and this might increase preference for the stimulus due to the relatively ease of processing. The results of this exploratory study showed that symmetrical versions of 3D novel objects were preferred for both haptics and vision even if participants were not encouraged to attend to symmetry. However, contrary to my expectations, preference for symmetry was not significantly greater for aligned relative to across objects though there was a trend in that direction for both modalities.

Part 1

Shape representation and object
recognition using raised line drawings

Chapter 2

2 Simultaneous sketching aids the haptic identification of raised line drawings

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2.1 Abstract

Haptically identifying raised line drawings is difficult. We investigated whether a major component of this difficulty lies in acquiring, integrating and maintaining shape information from touch. Wijntjes, van Lienen, Verstijnen, and Kappers (2008b) reported that drawings which participants had failed to identify by touch alone could often subsequently be named if they were sketched. Thus people sometimes needed to externalise haptically acquired information by making a sketch in order to be able to use it. We extended Wijntjes et al.'s task and found that sketching whilst touching improved drawing identification even more than sketching after touching, but only if people could see their sketches. Our results suggest that the slow, serial nature of information acquisition seriously hampers the haptic identification of raised line drawings relative to visually identifying line drawings. Simultaneous sketching may aid identification by reducing the burden on working memory and by helping to guide haptic exploration. This conclusion is consistent with the finding that 3D objects are much easier to identify haptically than raised line drawings since, unlike for vision, simultaneously extracting global shape information is much easier haptically for 3D stimuli than for line drawings (Lawson & Bracken, 2011).

2.2 Introduction

Have you ever tried to use your hand like a scanner? Probably not, but if you try it, you will discover that your fingers are easily able to identify familiar 3D objects in the absence of vision. Klatzky, Lederman and Metzger (1985) showed that people are both fast (often taking under 2s) and accurate at naming everyday objects using haptics (active touch). In contrast, it is well-established that both sighted and congenitally blind people find it difficult to identify raised line drawings using touch alone (e.g., Heller, 1989; Heller, Calcaterra, Burson & Tyler, 1996; Kennedy & Bai, 2002; Klatzky, Loomis, Lederman, Wake & Fujita, 1993; Lawson & Bracken, 2011; Lederman, Klatzky, Chataway & Summers, 1990; Loomis, Klatzky & Lederman, 1991; Picard & Lebaz, 2012). Error rates at naming such drawings are often over 50% and response times over a minute. In contrast, visually presented line drawings representing everyday objects are usually easy and quick to identify (Lawson & Jolicoeur, 2003; Snodgrass & Vanderwart, 1980).

It is not yet fully understood why line drawings are so much harder to identify by haptics than by vision. There are a number of possible reasons. One factor is that line drawings do not unambiguously specify the shape of 3D objects and this may be particularly detrimental for touch since depth cues are more important for haptics than for vision. For example, Lawson and Bracken (2011) found that the error rate for identifying 3D models of familiar objects (25%) was less than half that of matched line drawings of the same objects (65%) and response times were also faster (7s versus 10s). A second issue is that line drawings are simplified or impoverished stimuli in contrast to everyday 3D objects (Lederman & Klatzky, 1987). For example, they do not provide useful information about texture, material, weight and size and these cues may be more important for haptics than for vision. A third reason is the greater time needed to explore line drawings by haptics compared to vision. Line drawings are mainly explored haptically by following the contours and this typically takes many seconds (Lawson & Bracken, 2011; Symmons & Richardson, 2000; Wijntjes, van Lienen, Verstijnen & Kappers, 2008a). In contrast, line drawings can usually be visually identified in a fraction of a second and with no need for eye movements. For example, Lawson and

Jolicoeur (2003) reported that even low contrast, immediately masked line drawings of upright views of objects could usually be identified with presentation durations under 100ms.

In the present study we examined the possible consequences of this third factor for the haptic perception of raised line drawings. Since haptic information is usually acquired from only a small portion of a drawing at a time it must be accumulated and maintained for a long time whilst the drawing is fully explored. People are quite accurate at integrating spatial information from touch across several seconds (Moscatelli, Naceri & Ernst, 2014). Nevertheless, this slow, serial acquisition of haptic information is likely to hamper processing. Analogously, visual processing is known to suffer when the field of view is restricted to force serial exploration of stimuli. Indeed, the accuracy of visual object recognition through a narrow aperture can be reduced to be similar to that of haptic object recognition (Craddock, Martinovic & Lawson, 2011; Loomis et al., 1991).

In the present study we investigated whether problems caused by only feeling one small part of a raised line drawing at a time could be alleviated by sketching during exploration to externalise the drawings. Externalisation means to make an external representation of an internal, mental representation. In this paper externalisation refers to people making visual sketches based on haptically perceived inputs; in the wider literature externalisation often refers to making visual sketches based on mental images (e.g., Pearson & Logie, 2014). However, externalisation need not involve making visual sketches. For example, a verbally described stimulus could be haptically externalised by moulding an unseen blob of plasticine. Note that perceiving externalisations produced in the same modality as the input modality is likely to lead to similar problems as are found when perceiving the original stimulus. Evidence for this in haptics comes from Experiment 2 of Wijntjes, van Lienen, Verstijnen, and Kappers (2008b). They found that using a raised line drawing kit to make a haptic sketch did not aid identification of drawings which people had just explored haptically. Only 4% of previously unidentified objects were identified in this haptic externalisation condition.

This study by Wijntjes et al. (2008b) motivated the present one. They reported that raised line drawings which people had failed to identify haptically could sometimes subsequently be identified if, after removing the

drawings, people sketched the drawings that they had just felt. Here, people could look at their sketches as they made them. In a control condition, people again sketched after haptic exploration of the line drawings but they were blindfolded so they never saw their sketches. This condition equated the time available to identify the drawings. However, only 2% of previously unidentified objects were identified in this control condition, compared to 31% when the sketch was visible. Wijntjes et al.'s results show that quite often people had stored sufficient information to support haptic identification of raised line drawings but they could not interpret it until it was externalized by producing a visible sketch. More generally, externalisation is known to aid both the identification of ambiguous pictures presented visually (such as the rabbit/duck stimulus; Chambers & Reisberg, 1985) and the identification of mental images constructed from verbal instructions (Finke, Pinker & Farah, 1989).

The results of Wijntjes et al. (2008b) leave open the question of the stage at which people fail to haptically identify line drawings. People could encounter problems during the early processes of guiding exploration, acquiring and maintaining haptic information and then integrating it into a global shape (Loomis et al., 1991). Alternatively, their main difficulty could lie a later stage, when they try to match the percept to an object representation stored in long-term memory (Heller et al., 1996). Predictions based on these two alternatives were compared in the present study. In the former case, identification during the initial exploration stage could be helped by externalising haptic information as it was being acquired, with a sketch of the whole stimulus gradually emerging over time. For example, externalisation (sketching) could help to focus exploration on the most important parts of the drawing. It could also reduce the need to integrate and maintain information in working memory. In contrast, in the latter case although sketching would, again, be predicted to lead to an identification advantage this advantage should not depend on when externalisation (sketching) occurs. This is because the latter account proposes that the main difficulty in haptically identifying raised line drawings is in matching the percept to representations in long-term memory.

Results from a recent experiment by Kalia and Sinha (2011) support the former explanation. They found that the haptic identification of raised line drawings correlated with the complexity and symmetry of the drawings whereas measures of image agreement and familiarity had little influence on haptic identification. They therefore argued that successful identification reflected early processes involved in integrating shape information rather than subsequent object matching processes. In the studies of both Wijntjes et al. (2008b) and Kalia and Sinha (2011), all of the information extracted during haptic exploration had to be stored in memory before sketching began. Studies measuring neural activity during exploration by touch suggest that there is a substantial burden on working memory as the haptic percept is built up (Grunwald, Weiss, Krause, Beyer, Rost, Gutberlet & Gertz, 1999; Martinovic, Lawson & Craddock, 2012). We investigated whether externalization through sketching might reduce this burden by letting people sketch during haptic exploration rather than sketching starting only after exploration.

We tested the haptic identification of raised line drawings across three conditions. The control, only-touch-before-sketch condition replicated the experimental condition tested by Wijntjes et al. (2008b). Here, people explored a raised line drawing haptically for 45s. The drawing was then removed and they had a further 30s to sketch what they had just felt; their sketch was visible in this second part of the trial. They tried to identify the drawing throughout both parts of the trial but only in the second part did a sketch provide a visible record of what they had perceived haptically. Just the first part of the trial differed for the other two conditions tested. In the second, visible-sketch+touch condition people sketched the drawing as they felt it in the first 45s of each trial. Here, people could see their sketch as it emerged during haptic exploration so they did not need to remember what they had felt, unlike the control, only-touch-before-sketch condition. If the cost of keeping information in working memory makes raised line drawings difficult to identify haptically then identification should be superior in this condition relative to the control condition. This condition might also aid people to explore the drawing more effectively, for example by helping to direct their fingers to the most critical areas. The final, unseen-sketch+touch condition checked whether it was difficult to combine sketching with one hand and using the other hand to feel a drawing. To test this, the first 45s of each trial

was identical to the visible-sketch+touch condition except that people could not see their sketch so they were not expected to benefit from making it. Performance here should be worse than in the control condition if it was hard to sketch at the same time as exploring the drawing.

We used two versions of each raised line drawing. They differed with respect to the salience and ease of tracking the lines by touch. The thermoform stimuli were similar to those used in most previous studies using raised line drawings. The lines were less than 1 mm high and were difficult to follow so haptic exploration was slow. In contrast, the plastic drawings had lines which were at least 6 mm high, and which were faster and easier to trace around. Lawson, Boylan and Edwards (2014) used similar stimuli and reported that people were much slower and less accurate at exploring thermoform (37s median correct reaction time, 25% correct) than plastic (20s, 41%) stimuli. We predicted that any benefit of sketching during exploration should be greater for the thermoform stimuli since exploration should be slower. This should increase the burden of integrating and maintaining a representation of the drawing as it is felt.

2.3 Method

2.3.1 Participants

36 students (26 females and 10 males, age range 18-30 years old) from the University of Liverpool volunteered to take part in the experiment, with most receiving course credit. All participants reported being right-handed, having normal or corrected-to-normal vision, and no known conditions affecting touch perception.

2.3.2 Stimuli

Each participant felt 27 drawings which depicted outlines of familiar, nameable objects, see Figure 1. The outline is the same as the occluding contour of an object at an infinite viewing distance, i.e. in parallel projection. Two versions of each drawing were produced, one with thermoform lines and

the other with plastic lines. In 24/27 cases both versions had identical outlines. The remaining three cases differed as matched pairs were not available, see Figure 1. The thermoform lines were printed on swell paper and were 1 mm tall x 2 mm across. The plastic lines were printed in ABS plastic using a 3D printer and were an average of 20 mm tall (minimum 6 mm) x 2 mm across. Each drawing was mounted onto a rigid base (140 mm horizontal x 120 mm vertical). All stimuli had dimensions greater than 40 mm x 60 mm and fitted inside this base except for the hammer and scissors which had a maximum extent of 200 mm and so extended beyond the base.

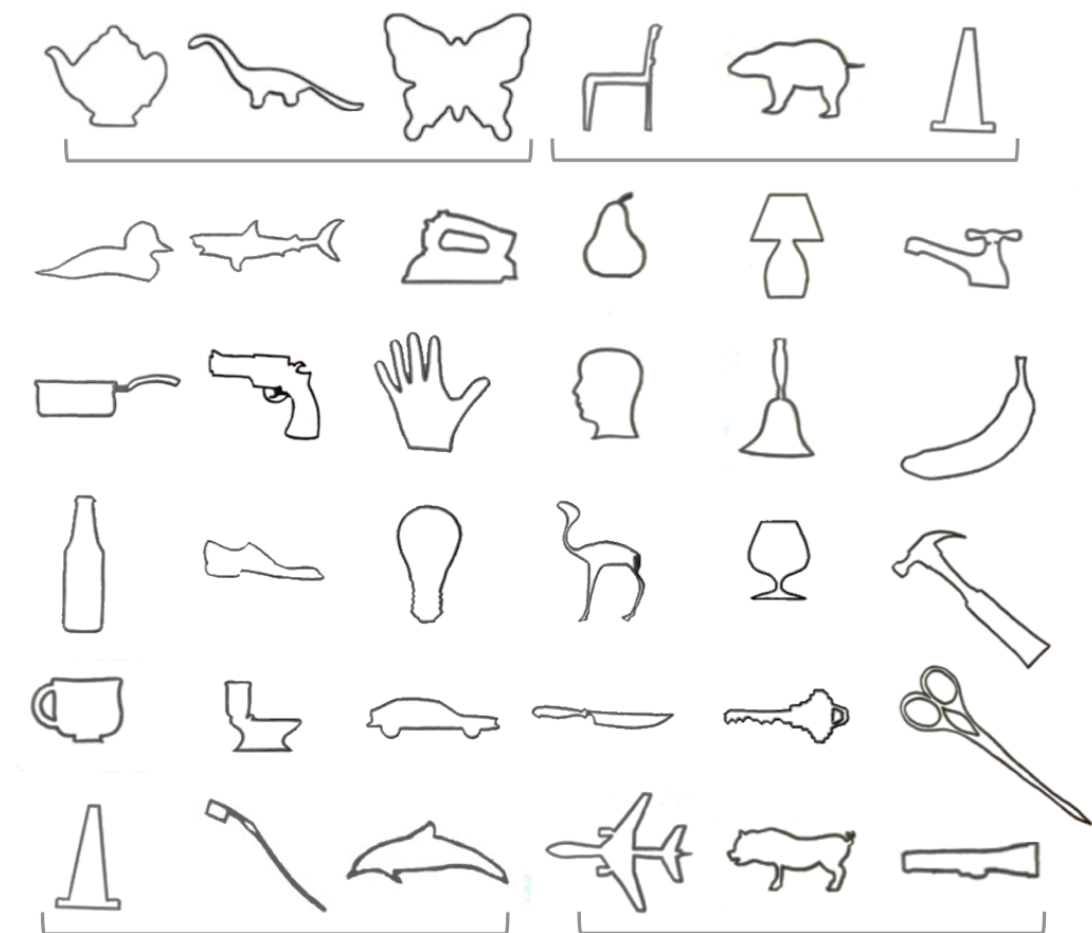


Figure 1. The drawings representing the outlines of familiar objects which were used in the study. The top row shows the practise stimuli for the plastic line versions (teapot, dinosaur and butterfly) and the thermoform versions (chair, bear and cone). The remaining rows show the experimental stimuli. These were identical for the plastic line and thermoform versions except for the three pairs on the bottom row (the cone, toothbrush and dolphin were used for the plastic line versions; the aeroplane, pig and torch for the thermoform versions). From the second row the remaining experimental

drawings depict a duck, shark, iron, pear, lamp, tap, saucepan, gun, hand, head, bell, banana, bottle, shoe, lightbulb, camel, glass, hammer, cup, toilet, car, knife, key and scissors.

2.3.3 Design and procedure

There were two main factors. There was a between-subjects factor of stimulus (thermoform lines and plastic lines) with 18 people randomly assigned to feel each type. There was also a within-subjects factor of sketching condition (control, only-touch-before-sketch; visible-sketch+touch; unseen-sketch+touch). All participants felt each of the 27 stimuli once. The stimuli were divided into three sets of nine items. The order of allocation of item set to each of the three sketching conditions and the order of presentation of these conditions within the experiment were both counterbalanced using a Latin Square design. For each pair of participants assigned to a given Latin Square condition, items were presented in one order for one participant and the reverse order for the other participant.

Participants were tested individually at a desk in a quiet laboratory. They sat to the right of a 50 cm tall barrier which blocked their view to the left. Drawings were placed into a slot on the left of the barrier and were explored by the left hand, see Figure 2. There were no instructions as to how to explore but most participants appeared to use just one finger. Sketching was done on the right of the barrier using the right hand only. Each sketch was made on a separate sheet of paper (150 mm horizontal x 105 mm vertical) placed into a slot. The primary task was to name each drawing as quickly as possible.

At the beginning of each trial participants rested their left index finger on the lower left corner of the left slot. The computer program then triggered a voice saying "Go now" which was their signal to start to feel the drawing for 45s. A beep sounded 30s after the start of this exploration to indicate that there was only 15s remaining. Another beep sounded at the end of the 45s. Participants stopped feeling the drawing and any sketch that they had made was removed. The three sketching conditions only differed in this first 45s of each trial. During this first 45s, no sketching was done in the control, only-touch-before-sketch condition whereas sketches were made in both the visible-sketch+touch condition (where the sketch was visible) and in the

unseen-sketch+touch condition (where the sketch and the participant's right hand were both hidden by a cover).

The second part of each trial was identical for all three sketching conditions. Participants had 30s to produce a visible sketch of the drawing that they had just felt. In the control, only-touch-before-sketch condition this was the first sketch to be made. In the visible-sketch+touch and the unseen-sketch+touch conditions a new, second sketch was produced during this 30s. A beep sounded at the end of the 30s period.

Participants could try to identify the object at any point during the trial. The experimenter pressed the spacebar as soon as the participant correctly named the object. Participants were told if their response was correct. Participants began by doing three practice trials in the same sketching condition as the first condition they were assigned to. Unlike the experimental trials, the practice drawings were shown visually to the participant after the practise. Participants then did 27 experimental trials which comprised three blocks of nine trials, one for each of the three conditions. The experiment lasted approximately 40 minutes.

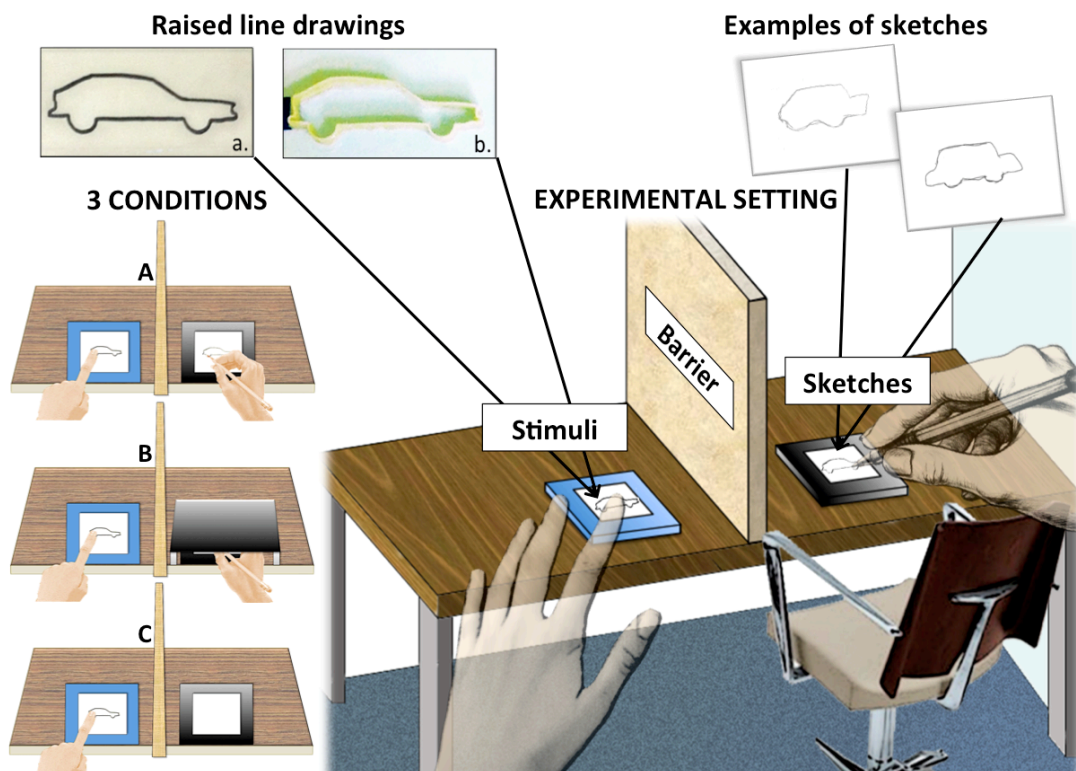


Figure 2. From the top left corner, examples of (a) the thermoform line and (b) the plastic line drawings. Below, illustration of the difference between the three sketching

conditions during the initial 45s of haptic exploration for: (A) visible-sketch+touch, (B) unseen-sketch+touch and (C) control, only-touch-before-sketch conditions. In the centre, the experimental setting is depicted with two sample sketches of the car from the first 45s of the trial in the visible-sketch+touch condition.

2.4 Results

No participant reported having seen any of the drawings prior to or during the experiment. One participant in the thermoform group identified just one drawing and was replaced. As expected, people found the stimuli difficult to identify so our primary analysis was for accuracy although we also report reaction times (RT) below. Only identifications that were correct at the first attempt were included as correct. We analysed separately the correct identifications which occurred in the first part of the trial (45s of haptic exploration) and the second part of each trial (30s of sketching without feeling the stimulus), see Table 1.

	First 45s of trial				Remaining 30s of trial		
	V	U	C		V	U	C
Thermoform lines (n=18)	40	25	25		21	15	18
Plastic lines (n=18)	73	57	64		8	7	11

Table 1. The number of correct identifications which occurred during the first 45s of the trial and during the remaining 30s of the trial in each of the three sketching conditions (visible-sketch+touch - V; unseen-sketch+touch - U; and control, only-touch-before-sketch - C) for the groups presented with thermoform lines and with plastic lines. To illustrate the relation of this data to that shown in Figure 3, if we ignore whether a correct response occurred in the first 45s or the remaining 30s of a trial, the total number of trials in each of the six cells was 18 participants x 9 drawings per condition, so 162 trials. Thus overall accuracy for the thermoform lines in the V condition was $(40+21) = 61$ trials out of 162 trials = 38%. This comprises 25% correct in the first 45s of the trial, as plotted in Figure 3, and 13% in the remaining 30s of the trial.

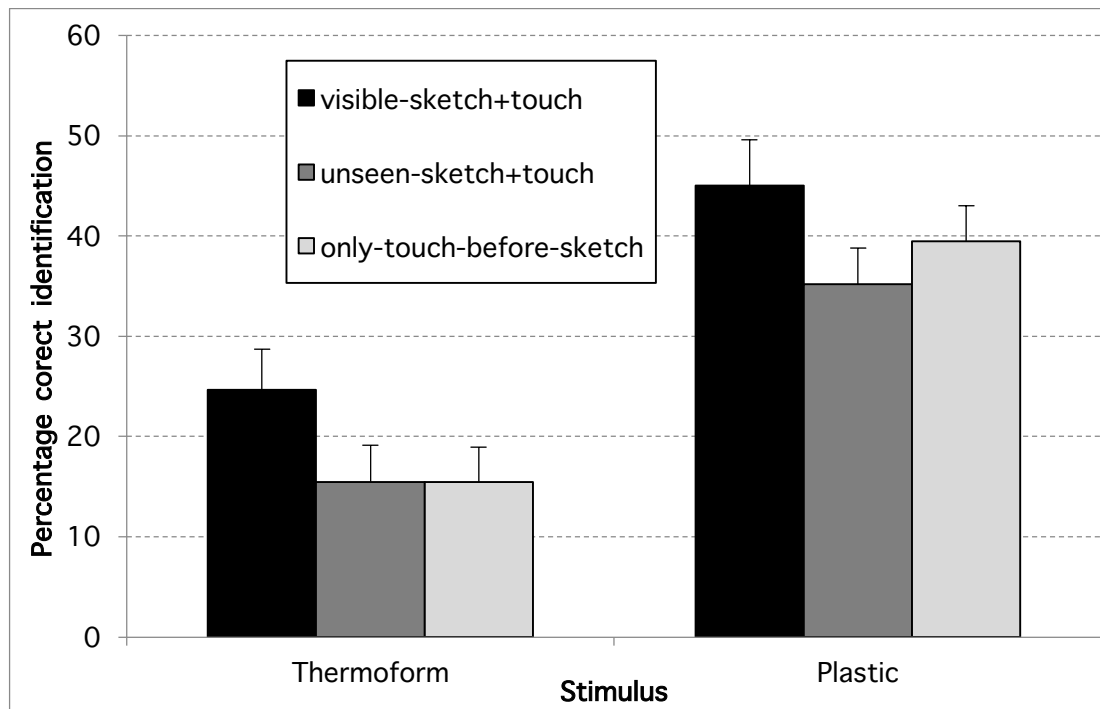


Figure 3. Percentage of correct identifications of the raised line drawings in the first 45s of the trial (when haptic exploration occurred) for each of the three sketching conditions for thermoform lines and plastic lines. Error bars represent the standard error of the mean.

An analysis of variance (ANOVA) of the percentage of correct identification in the first 45s of the trial revealed a significant effect of stimulus, $F(1,34) = 23.917, p < .001$, partial $\eta^2 = .41$, with greater accuracy for plastic (40%) than thermoform (19%) stimuli. There was also a significant effect of sketching condition, $F(2,68) = 4.934, p = .01$, partial $\eta^2 = .13$. Post-hoc Newman-Keuls analyses revealed significant differences (at $p < .05$) between the visible-sketch+touch condition (35%) and both the unseen-sketch+touch condition (25%) and the control, only-touch-before-sketch condition (27%). There was no significant difference between the latter two conditions. Finally, the interaction between sketching condition and stimulus was not significant, $F(2,68) = 0.268, p = .8$, partial $\eta^2 = .01$, see Figure 3.

We checked whether the advantage for the visible-sketch+touch condition occurred simply because it allowed people to produce visible sketches earlier in the trial. If so then identification which would otherwise have occurred during the final 30s of the trial (when people produced visible sketches in all three conditions) would instead have occurred in the first 45s

of the trial (when people only produced a visible sketch in the visible-sketch+touch condition). If this was the case then performance in the final 30s of the trial should be better for the unseen-sketch+touch and the control, only-touch-before-sketch conditions as they caught up. In contrast, performance should be similar across all three conditions in the final 30s of the trial if, as we propose, early processes involved in acquiring, maintaining and integrating haptically acquired information were easier in the visible-sketch+touch condition.

There was no evidence to support the former prediction. We considered only the correct responses that occurred in the final 30s of the trial, and averaged over results for the plastic and thermoform lines. The visible-sketch+touch condition had just as many extra correct identifications (9%) as the control, only-touch-before-sketch condition (9%) and the unseen-sketch+touch condition (7%). As a percentage of the drawings that had not already been identified in the first 45s of each trial these extra identifications were 14%, 12% and 9% respectively.

Finally, we analysed mean RT when the participant's first guess was correct, whenever that occurred in a trial. There were six empty cells in this analysis, all for the thermoform group. These cells were replaced by the mean for the appropriate condition. Stimulus was significant, $F(1,34) = 26.390$, $p < .001$, partial $\eta^2 = .44$. RT to plastic lines (26s) were much faster than to thermoform lines (40s), consistent with Lawson et al. (2014). There was no significant effect of sketching condition and no interaction of stimulus x sketching condition ($F < 1$, $p > .5$, partial $\eta^2 < .01$ in both cases). This analysis was repeated including RT for incorrect as well as correct trials. The pattern of results was unchanged: stimulus was significant, $F(1,34) = 34.870$, $p < .001$, partial $\eta^2 = .51$. RT to plastic lines (46s) were much faster than to thermoform lines (61s) and there was no significant effect of sketching condition of the interaction of stimulus x sketching condition.

2.5 Discussion

Wijntjes et al. (2008b) found that some raised line drawings that participants could not identify haptically could later be identified if

participants sketched what they had just felt. We, too, found that some drawings that were not identified as they were being explored were later identified during the second part of the trial. The magnitude of this benefit due to externalisation (around 11% of possible trials) was less than that reported by Wijntjes et al. (2008b), who found that 31% of possible trials were identified by novice sketchers, or by Kalia and Sinha (2011), who found that 27% of possible trials were identified by naive observers shown sketches done by expert sketchers. Given the many differences across these three studies we do not wish to speculate on why the benefit of post-exploration sketching might vary in magnitude.

Making a sketch whilst haptically exploring a line drawing did not significantly disrupt identification even though participants had to control the movements of both of their hands. Identification accuracy during haptic exploration was similar when the right hand had to sketch, in the unseen-sketch+touch condition (25%), and when the right hand was inactive, in the control, only-touch-before-sketch condition (27%).

Most importantly, we found that an extra benefit from externalisation occurred if a visible sketch was produced during the first, exploratory part of the trial, whilst the line drawing was being touched. During this first period accuracy in the visible-sketch+touch condition (35%) was significantly greater than in the unseen-sketch+touch condition (25%) demonstrating that it was not enough to make a sketch: people needed to see it to benefit from it.

Performance in the second, non-exploratory 30s of each trial showed similar levels of extra identifications across all three conditions. If the early externalisation which was available only in the visible-sketch+touch condition had merely sped up the identification of raised line drawings then performance in the unseen-sketch+touch and control, only-touch-before-sketch conditions should have caught up with that in the visible-sketch+touch condition in this second, non-exploratory phase. There was no evidence to support this proposal.

In our study in all three conditions participants felt a raised line drawing and in all three conditions they drew a visible sketch of what they had felt. The only difference between the three conditions was *when* participants first sketched the drawing (during exploration versus after exploration) and *when* they could first see their sketch (during exploration

versus after exploration). Our results showed that sketching during exploration was more useful than sketching after exploration but only if the sketch was visible. A likely reason why externalisation aided performance in the first, exploratory part of the trial in the visible-sketch+touch condition was by reducing the burden on working memory processes involved in maintaining and integrating haptically acquired information (Loomis et al., 1991). Sketching during exploration may also have improved exploration, for example by directing the hands to touch more informative areas of the drawing.

Most studies of the haptic identification of raised line drawings have used shallow lines such as thermoform stimuli². We also used thermoform stimuli but in addition we presented plastic line stimuli which were easier to explore (Lawson et al., 2014). People were both faster and more accurate at naming the plastic (26s, 40% correct) than the thermoform (40s, 19%) line drawings during the first, exploratory part of the trial. This finding has important practical implications for the design of stimuli intended to be explored haptically, such as tactile diagrams. We advise that, where possible, raised line drawings and diagrams designed for the visually impaired should use similar lines which are easy and rapid to follow. Recent advances in 3D printing technology have made such lines much cheaper and simpler to produce.

We did not find an interaction between our manipulation of stimulus type and the externalisation benefit. We had expected that the thermoform stimuli would show a greater benefit of externalisation during exploration because they were harder to explore. The lack of an interaction could be because even the plastic line drawings were difficult to identify. These stimuli typically took tens of seconds to name so the burden on processes such as guiding exploration and working memory presumably remained high so here, too, externalisation helped.

In this study raised line drawings were easier to identify if people could sketch them as they felt them. This result is consistent with examples of how externalization can aid mental imagery in the visual perception literature (e.g., Verstijnen et al., 1998) though strong benefits have not always been found (e.g., Anderson & Helstrup, 1993). For instance, Chambers and Reisberg (1985)

presented ambiguous stimuli such as the Necker cube and the rabbit/duck figure and asked participants to use mental imagery to identify the other referent. Participants could not reverse these figures whereas they usually succeeded at reinterpreting them after sketching them on paper. Similarly, Finke, Pinker and Farah (1989) gave verbal instructions to their participants to create mental images such as imagining the letter D on its side, fixed to the top of the letter J. Participants often reported perceiving the shape of an umbrella so they could transform and reinterpret mental images. However, on the trials where people failed to identify the shape using mental imagery they often then did identify it after sketching (83% of the time). Here, again, externalisation improved performance.

Our results have shown that externalisation can aid haptic identification. We suggest that simultaneous sketching is helpful in reducing the difficulties that haptic perception has in the early stages of processing when spatial information must be sequentially acquired, maintained and integrated in working memory. It remains for future research to determine whether externalisation improved performance by guiding exploration and/or by reducing the burden on memory and whether externalisation would also aid performance for participants who were skilled or trained in 2D haptic perception. In addition, here we investigated the haptic identification of raised line drawings. Future work should also examine whether similar results occur for 3D objects, particularly for large, novel or complex shapes which require several seconds to fully explore.

Footnote

1 This ANOVA was repeated but using combined data from the whole trial (the first, 45s exploration phase and the second, 30s sketching phase). The pattern of results was the same and the main effects of stimulus and sketching condition were still significant whilst the interaction of stimulus x sketching condition remained non-significant ($F < 1$, $p = 0.5$, partial $\eta^2 < .03$).

2 The proper name of what we referred to as thermoform stimuli was *swell paper stimuli*.

Part 2

Shape representation and potential
cues to objectness: role of symmetry
and repetition

Chapter 3

3 Regularity detection by haptics and vision

* This study has been accepted for publication as: Cecchetto, S., & Lawson, R. (2016). Regularity detection by haptics and vision. *Journal of Experimental Psychology: Human Perception and Performance*. (In press)

3.1 Abstract

For vision, mirror-reflective 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.

3.2 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 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-reflective 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-reflective 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, Friedenber and Kubovy (1997; see also Friedenber & 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).

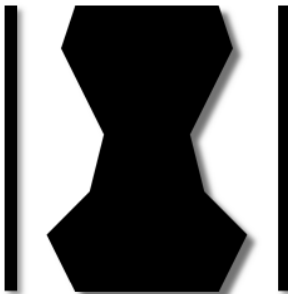
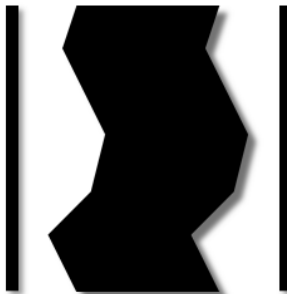


	symmetry	repetition
one - object		
two - objects		

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).

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).





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).

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 strategies¹.

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; Friedenbergs & 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. 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.

3.3 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.

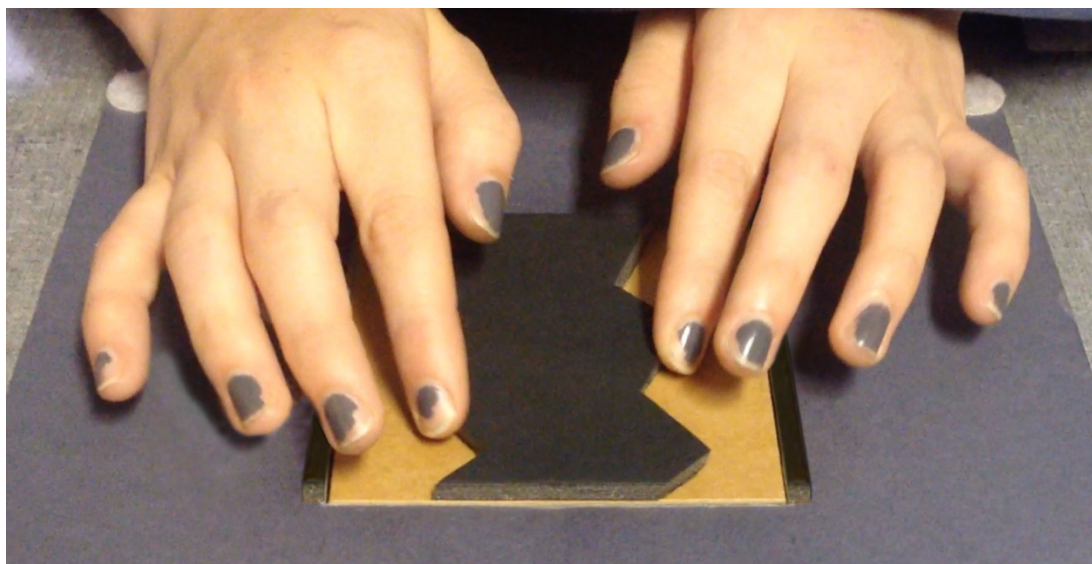


Figure 3. A participant feeling a repeated, aligned, one-object stimulus in Experiment 1.

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, Friedenbergh and Bertamini (2000) found weak alignment effects with a general trend for an alignment advantage for repetition detection as well as symmetry detection. Thus the prediction that axis

alignment should aid the visual detection of symmetry, but not of repetition, was supported by the results of Baylis and Driver (1994) and Farell (2015), but not by those of Friedenberg and Bertamini (2000).

Few studies have investigated the effects of axis alignment on haptic regularity detection. Cattaneo et al. (2010, 2013) found an advantage for remembering frontal views of 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 replicated and extended for explicit regularity detection by Lawson et al. (in press). We found that haptic symmetry detection was easier for aligned compared to across stimuli, whereas the haptic repetition detection showed no consistent effects of axis alignment. 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.

3.3.1 Method

3.3.1.1 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.

3.3.1.2 *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.

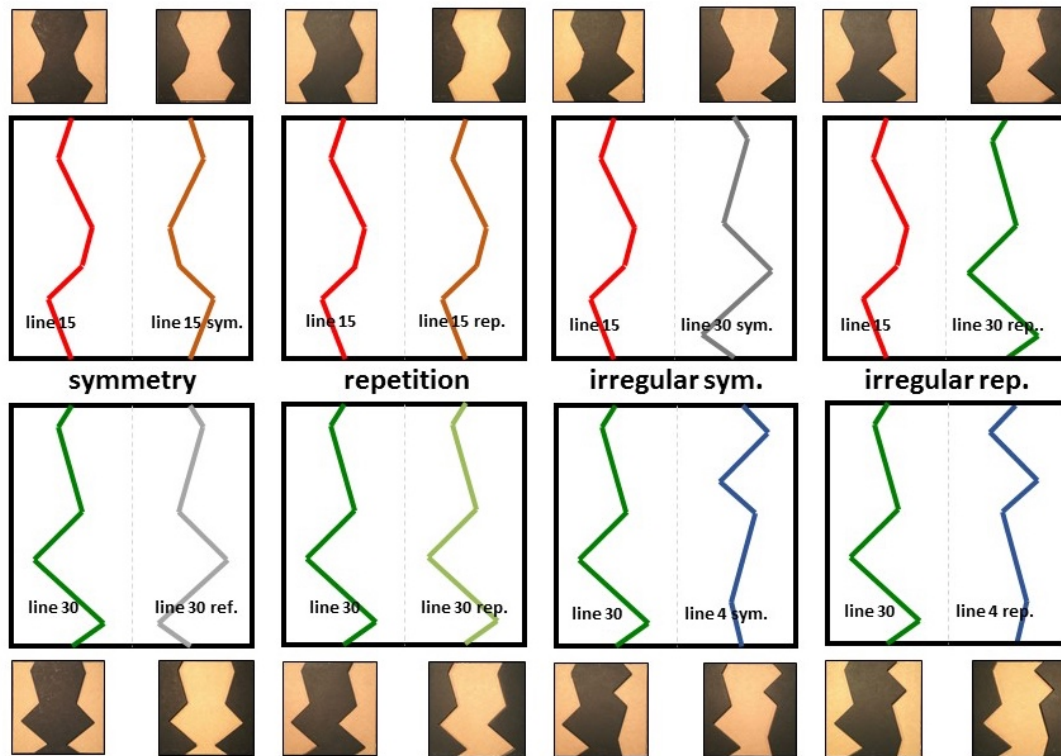


Figure 4. An illustration of how sets of stimuli were created for two of the 40 critical contours (line 15 and line 30). In the top half of the figure, line 15 was mirror-reflected and translated to produce the symmetrical and repeated stimuli respectively. Line 15 was also paired with a symmetrical 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).

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 in the same position as 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° to the left so that it ran across the body midline.

3.3.1.3 *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.

3.3.1.4 *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.

3.3.2 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 \times 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 \times alignment was not significant for RT [$F(1,30) = 2.18$, $p = .15$, partial $\eta^2 = .07$], but it was significant for errors [$F(1,30) = 18.32$, $p < .001$, partial $\eta^2 = .38$]. 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 \times alignment interaction that we reported in Lawson et al. (in press) for detecting regularity across critical lines only (rather than for 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 $\eta^2 = .57$], and errors [$F(1,15) = 60.14$, $p < .001$, partial $\eta^2 = .80$]. 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 $\eta^2 = .19$], or for errors [$F(1,15) = 0.81$, $p = .38$, partial $\eta^2 = .05$]. 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 \times objectness was not significant for RT [$F(1,15) = 0.06$, $p = .81$, partial $\eta^2 = .00$], or for errors [$F(1,15) = 0.00$, $p = .99$, partial $\eta^2 = .00$], see Figure 5.

For the across group, regularity-type was significant for both RT [$F(1,15) = 9.43$, $p = .008$, partial $\eta^2 = .39$], and errors [$F(1,15) = 10.05$, $p = .006$, partial $\eta^2 = .40$]. 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 $\eta^2 = .65$], and errors [$F(1,15) = 19.91$, $p < .001$, partial $\eta^2 = .57$]. 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 [$F(1,15) = 0.20, p = .66, \text{partial } \eta^2 = .02$], or for errors [$F(1,15) = 0.10, p = .76, \text{partial } \eta^2 = .01$], see Figure 5.

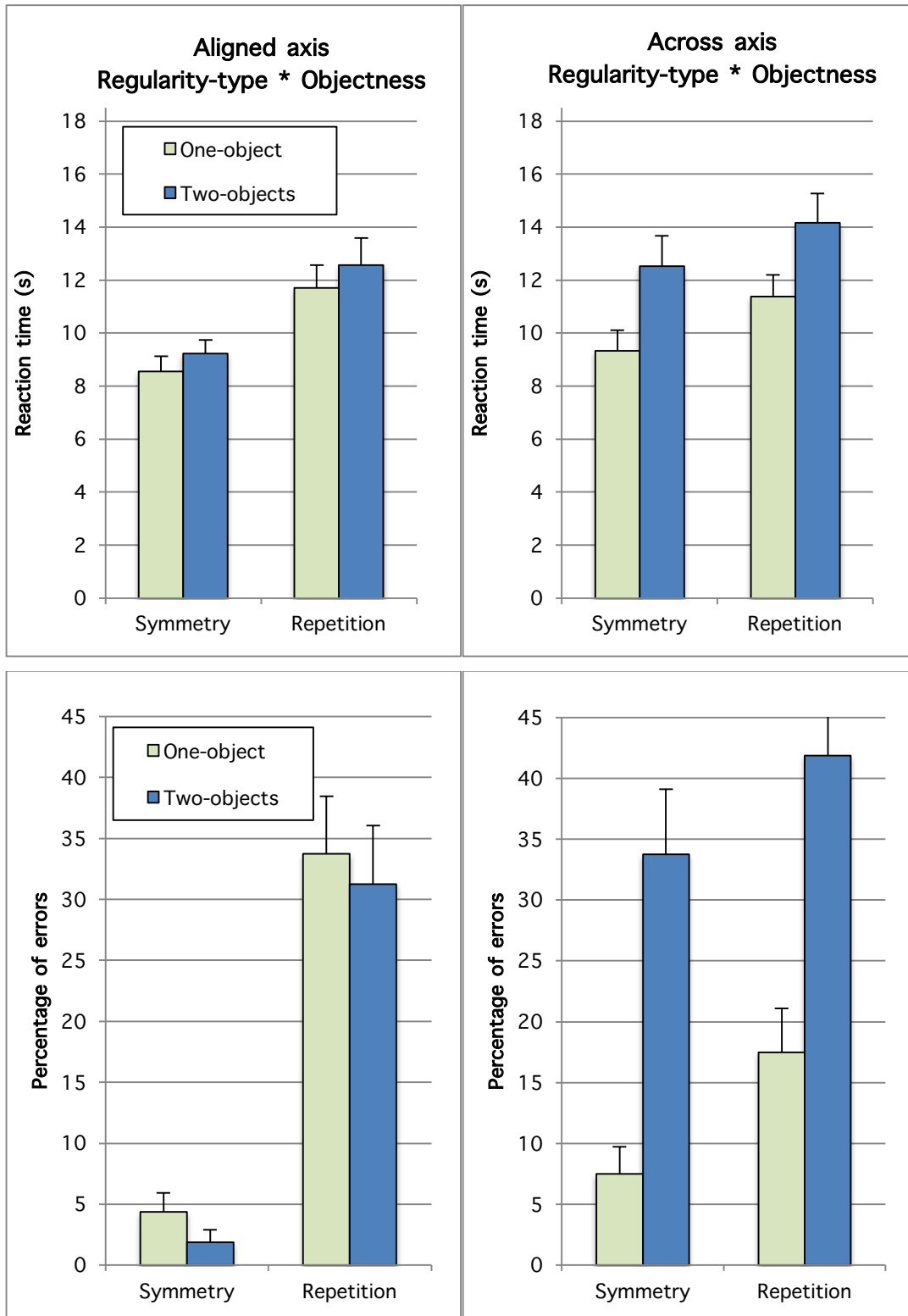


Figure 5. Results for regular trials for the haptic detection of regularities in Experiment 1. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark bars) stimuli with the axis of regularity aligned with (left graphs)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

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

3.4 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 view 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.

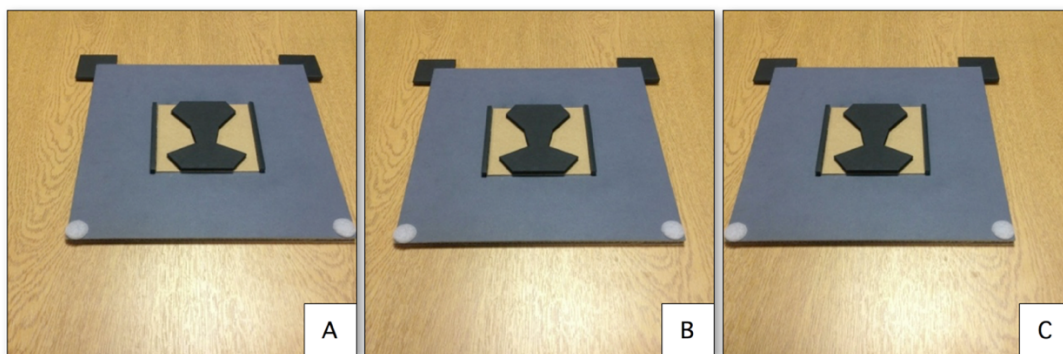


Figure 6. Slanted-view photos of the same symmetrical, one-object stimulus with the axis of regularity aligned to the body midline. Photos were taken from three different positions: A) left eye; B) central; C) right eye. Photos A and C were taken by translating the camera 3cm left and right respectively 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.

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; Farrell, 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.

3.4.1 Method

3.4.1.1 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.).

3.4.1.2 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 approximately 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 the right eye in the pictorial condition.



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

3.4.1.3 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.

3.4.1.4 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.

3.4.2 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 [$F(1,31) = 162.02, p < .001, \text{partial } \eta^2 = .84$], and errors [$F(1,31) = 84.19, p < .001, \text{partial } \eta^2 = .73$]. 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 [$F(1,31) = 66.82, p < .001, \text{partial } \eta^2 = .68$], and errors [$F(1,31) = 25.27, p < .001, \text{partial } \eta^2 = .45$]. 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 [$F(1,31) = 118.66, p < .001, \text{partial } \eta^2 = .79$], and errors [$F(1,31) = 73.26, p < .001, \text{partial } \eta^2 = .70$]. Detection was easier for symmetry (0.89s, 3%) than for repetition (1.56s, 15%). Objectness was significant for both RT [$F(1,31) = 24.86, p < .001, \text{partial } \eta^2 = .45$], and errors [$F(1,31) = 43.66, p < .001, \text{partial } \eta^2 = .59$]. 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 [$F(1,31) = 143.87, p < .001, \text{partial } \eta^2 = .82$], and errors [$F(1,31) = 75.54, p < .001, \text{partial } \eta^2 = .71$], 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 [$F(1,31) = 26.56, p < .001, \text{partial } \eta^2 = .46$], and errors [$F(1,31) = 4.39, p = .044, \text{partial } \eta^2 = .12$]. Detection was, again, easier for symmetry (0.95s, 4%) than repetition (1.19s, 7%). Objectness was significant for both RT [$F(1,31) = 24.66, p < .001, \text{partial } \eta^2 = .44$], and errors [$F(1,31) = 4.79, p = .036, \text{partial } \eta^2 = .13$]. 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 [$F(1,31) = 44.19, p < .001, \text{partial } \eta^2 = .59$], and errors [$F(1,31) = 20.62, p < .001, \text{partial } \eta^2 = .39$], 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.

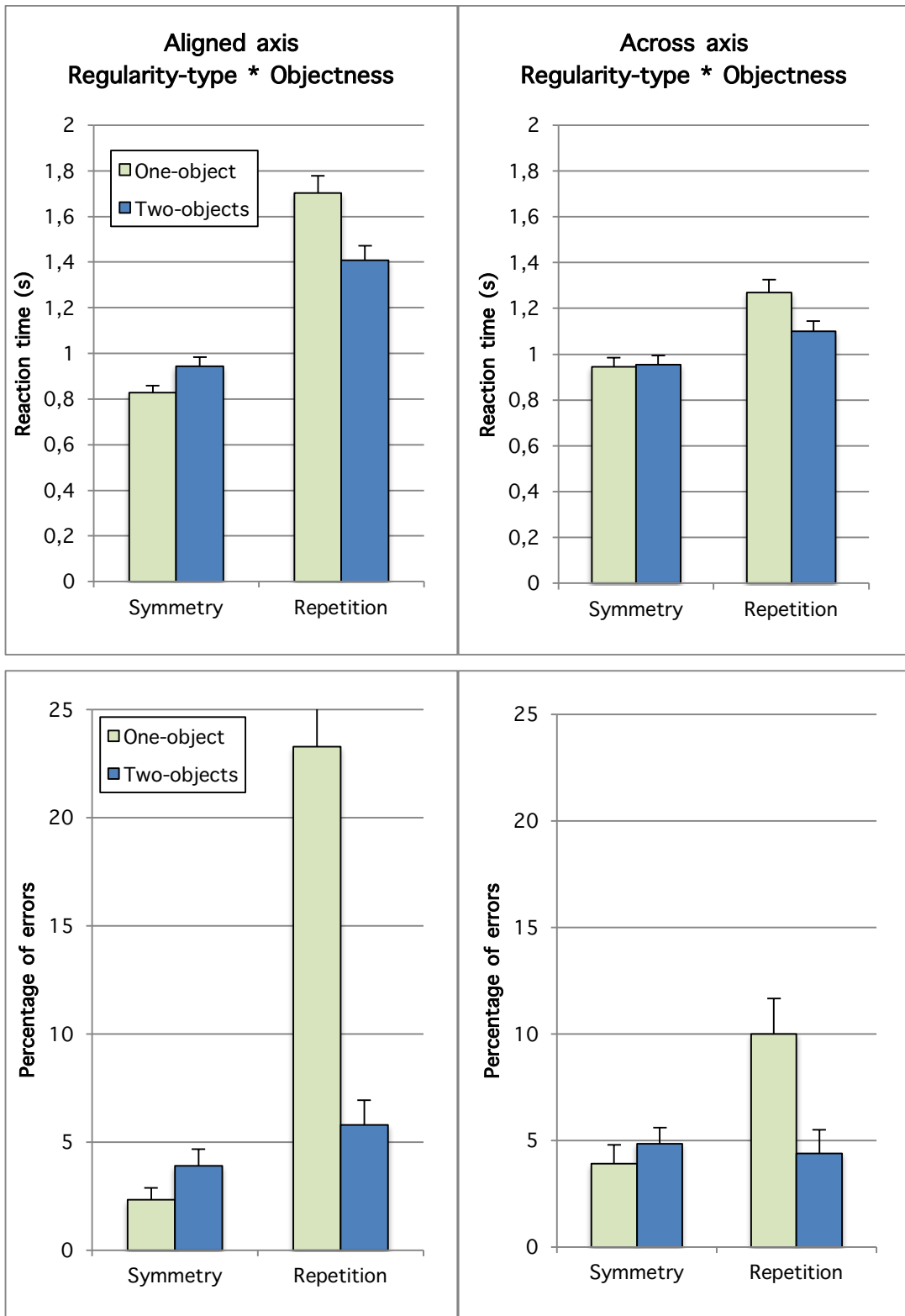


Figure 8. Results for regular trials for the visual detection of slanted views of regularities in Experiment 2. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark

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.

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. To try to understand why the results of Experiment 2 failed to support our prediction, in Experiment 4 we investigated whether the surprising across advantage for visual regularity detection was due to image-based distortions arising from the use of slanted rather than frontoparallel views.

3.5 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 recorded the exploration strategies used on a subset of the trials used in Experiment 1.

3.5.1 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, objectness influenced how most people explored across stimuli but 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).

3.5.2 Method

3.5.2.1 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.

3.5.2.2 *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.

3.5.2.3 *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).

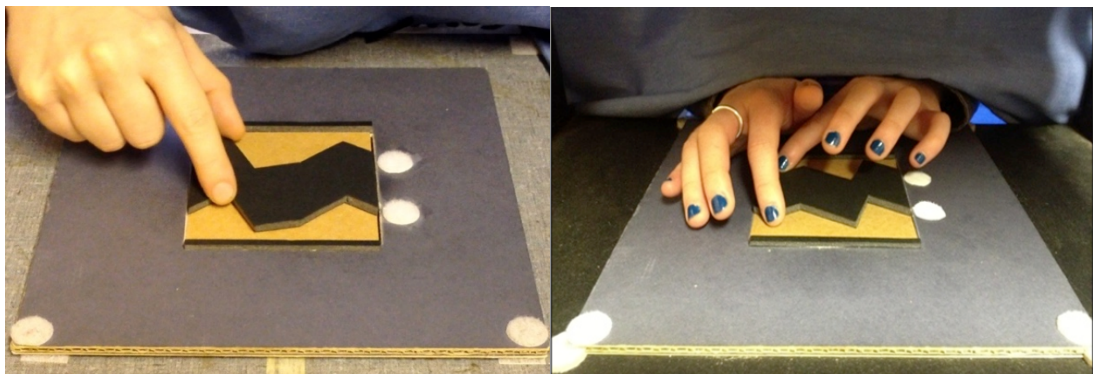


Figure 9. One-handed (left) versus two-handed (right) exploration conditions in Experiment 3. The stimuli were identical to those used in Experiment 1 except that the axis of regularity always ran across the participant's body midline. The resting positions, marked by two white round patches, were placed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

3.5.2.4 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.

3.5.3 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 [$F(1,45) = 3.46, p = .07, \text{partial } \eta^2 = .07$], or for errors [$F(1,45) = .05, p = .2, \text{partial } \eta^2 = .04$]. 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 one-handed exploration of across stimuli, regularity-type was significant for both RT [$F(1,15) = 5.81, p = .029, \text{partial } \eta^2 = .29$], and errors [$F(1,15) = 6.15, p = .025, \text{partial } \eta^2 = .29$]. Detection was easier for symmetry (9.8s, 21%) than repetition (11.5s, 28%). Objectness was significant for both RT [$F(1,15) = 24.25, p < .001, \text{partial } \eta^2 = .62$], and for errors [$F(1,15) = 17.35, p = .001, \text{partial } \eta^2 = .54$]. 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 [$F(1,15) = 2.36, p = .15, \text{partial } \eta^2 = .14$], or for errors [$F(1,15) = 1.35, p = .26, \text{partial } \eta^2 = .08$], see Figure 10.

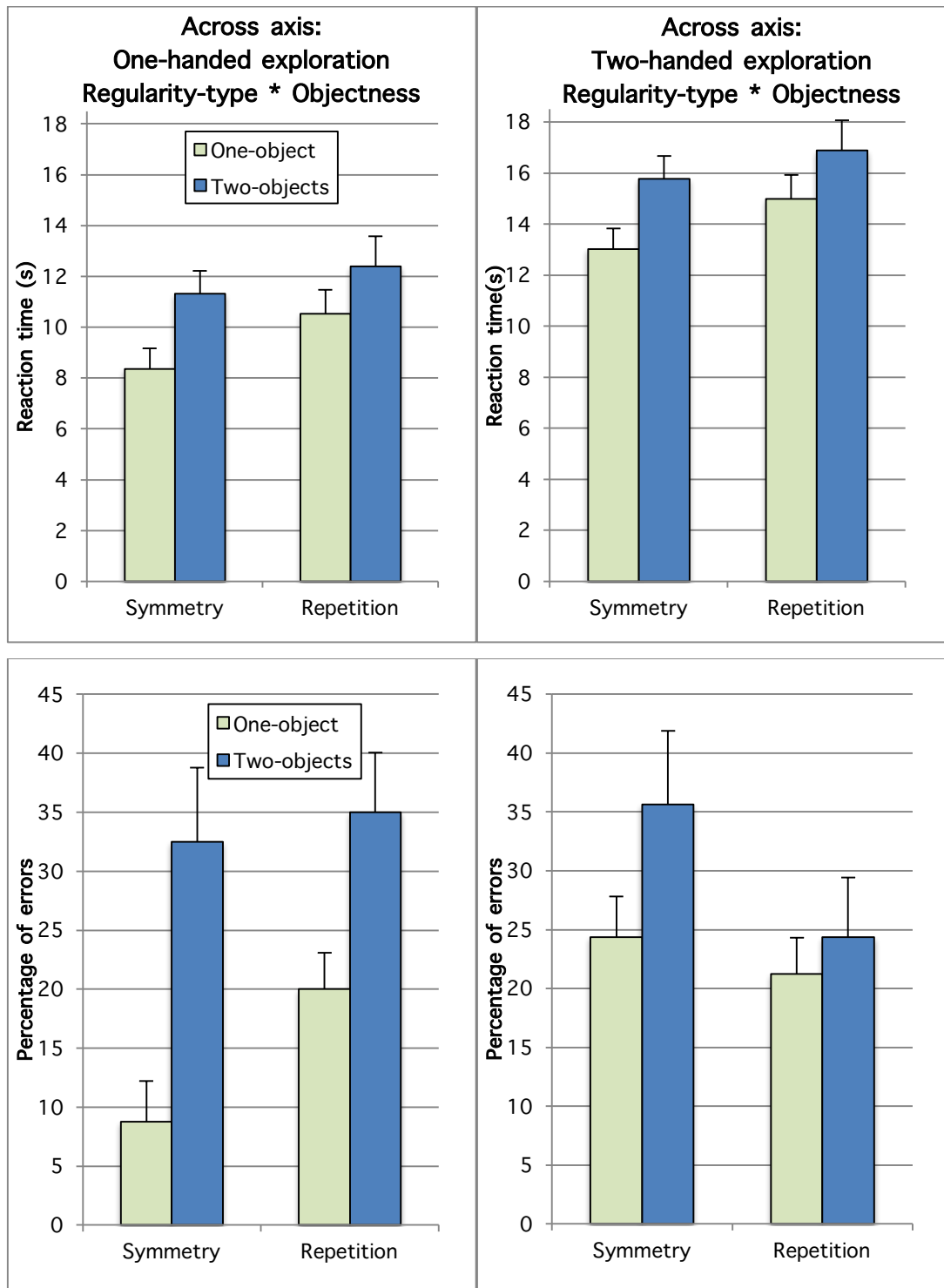


Figure 10. Results for regular trials, with the axis of regularity running across the body midline, for the haptic detection of regularities in Experiment 3. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark bars)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

graphs) or with two hands (right graphs). Error bars represent one standard error of the mean.

For two-handed exploration of across stimuli, regularity-type was not significant for either RT [$F(1,15) = 3.74, p = .072, \text{partial } \eta^2 = .20$], or errors [$F(1,15) = 3.22, p = .093, \text{partial } \eta^2 = .18$]. 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 [$F(1,15) = 27.17, p < .001, \text{partial } \eta^2 = .64$], but not for errors [$F(1,15) = 1.45, p = .25, \text{partial } \eta^2 = .09$]. 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 [$F(1,15) = 2.09, p = .17, \text{partial } \eta^2 = .12$], or for errors [$F(1,15) = 0.58, p = .46, \text{partial } \eta^2 = .04$], 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.

3.6 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 distortions 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 contour lines (Lawson et al., in press), these changes between slanted and frontoparallel views might have influenced the critical 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. Experiment 4 was conducted to test whether the surprising across advantage that we instead found in Experiment 2 was caused by the use of slanted views.

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, rather than a slanted, 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 the critical contours 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).

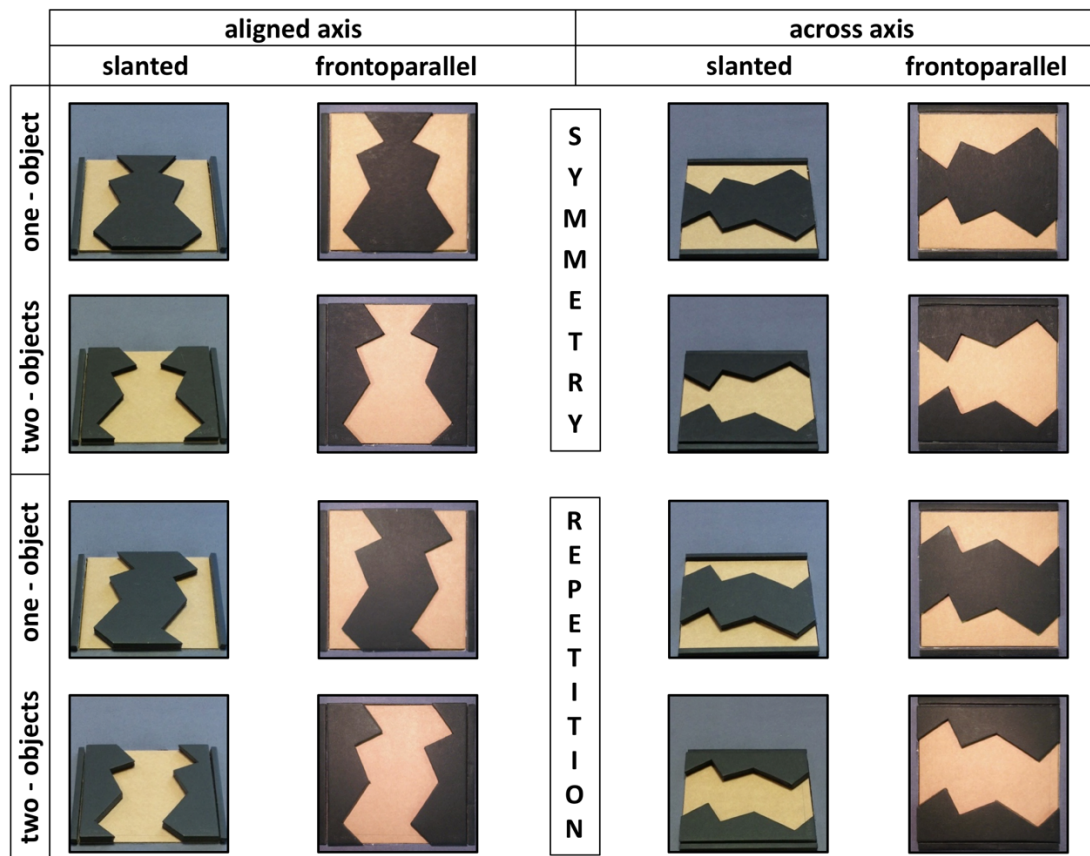


Figure 11. An illustration of the differences between the slanted views used in Experiment 2 and the frontoparallel views used in Experiment 4. All photos are scaled to equate the length at the base of the frame. The change in the location of the vertices in slanted views relative to frontoparallel views 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.

3.6.1 Method

3.6.1.1 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.

3.6.1.2 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.

3.6.2 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 [$F(1,31) = 91.66, p < .001, \text{partial } \eta^2 = .75$], and errors [$F(1,31) = 32.25, p < .001, \text{partial } \eta^2 = .51$]. 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 [$F(1,31) = 2.48, p = .125, \text{partial } \eta^2 = .07$], or for errors [$F(1,31) = .40, p = .53, \text{partial } \eta^2 = .01$]. 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, 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 [$F(1,31) = 86.74, p < .001, \text{partial } \eta^2 = .74$], and errors [$F(1,31) = 43.21, p < .001, \text{partial } \eta^2 = .58$]. Detection was easier for symmetry (0.78s, 3%) than repetition (1.19s, 11%). Objectness was significant for both RT [$F(1,31) = 24.62, p < .001, \text{partial } \eta^2 = .44$], and errors [$F(1,31) = 32.59, p < .001, \text{partial } \eta^2 = .51$]. 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 [$F(1,31) = 45.11, p < .001, \text{partial } \eta^2 = .59$], and errors [$F(1,31) = 47.14, p < .001, \text{partial } \eta^2 = .60$], 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 [$F(1,31) = 68.29, p < .001, \text{partial } \eta^2 = .69$], and errors [$F(1,31) = 43.17, p < .001, \text{partial } \eta^2 = .58$]. Detection was easier for symmetry (0.87s, 3%) than repetition (1.22s, 12%). Objectness was significant for both RT [$F(1,31) = 36.71, p < .001, \text{partial } \eta^2 = .54$], and errors [$F(1,31) = 19.22, p < .001, \text{partial } \eta^2 = .38$]. 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 [$F(1,31) = 68.47, p < .001, \text{partial } \eta^2 = .69$], and errors [$F(1,31) = 4.77, p = .037, \text{partial } \eta^2 = .13$], 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.

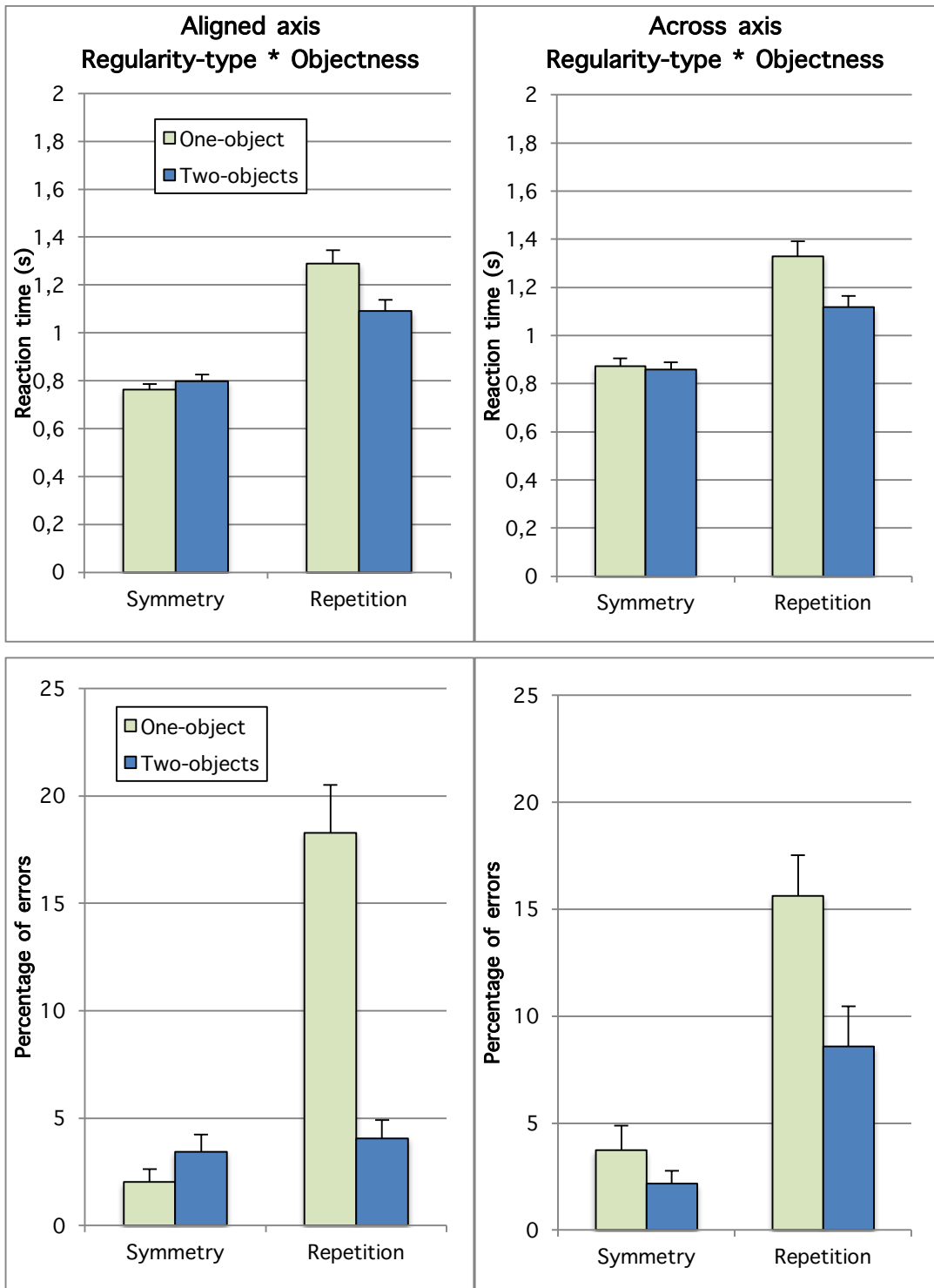


Figure 12. Results for regular trials for the visual detection of frontoparallel views of regularities in Experiment 4. Reaction time (top) and percentage of errors (bottom) for symmetry and repetition detection for one-object (light bars) and two-objects (dark bars) stimuli with the axis of regularity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

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 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.

3.7 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. Instead, 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 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 repetition as well as for detecting 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, including all of the studies discussed so far (Baylis & Driver, 1995; Bertamini et al., 1997; Bertamini, 2010; Friedenber

& Bertamini, 2000; Koning & Wagemans, 2009). These studies 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 will describe 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, in press) 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.

3.8 APPENDIX - Further analyses

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 [$F(1,30) = 28.80, p < .001, \text{partial } \eta^2 = .49$], errors [$F(1,30) = 65.61, p < .001, \text{partial } \eta^2 = .69$], and sensitivity [$F(1,30) = 102.23, p < .001, \text{partial } \eta^2 = .77$]. Detection was easier for symmetry (9.9s, 12%, d' of 2.15) than repetition (12.4s, 31%, 1.03). Objectness was significant for RT [$F(1,30) = 28.87, p < .001, \text{partial } \eta^2 = .49$], errors [$F(1,30) = 13.05, p = .001, \text{partial } \eta^2 = .30$], 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 \times 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 \times 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 \times 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 \times objectness \times 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.

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 \times regularity-type \times 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 because slanted rather than frontoparallel views were presented in Experiment 2.

Next, the remaining interactions are reported. The interaction of regularity-type \times 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 $\eta^2 = .73$], 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 \times alignment was significant for RT [$F(1,31) = 66.82, p < .001, \text{partial } \eta^2 = .68$], errors [$F(1,31) = 25.27, p < .001, \text{partial } \eta^2 = .45$], and sensitivity [$F(1,31) = 63.41, p < .001, \text{partial } \eta^2 = .67$]. 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 \times alignment was not significant for RT [$F(1,31) = 0.11, p > .74, \text{partial } \eta^2 = .01$], or for sensitivity [$F(1,31) = 0.01, p = .91, \text{partial } \eta^2 = .00$], but it was significant for errors [$F(1,31) = 9.09, p < .005, \text{partial } \eta^2 = .23$]. 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 \times objectness \times alignment for RT [$F(1,31) = 29.28, p < .001, \text{partial } \eta^2 = .49$], errors [$F(1,31) = 26.05, p < .001, \text{partial } \eta^2 = .46$], and sensitivity [$F(1,31) = 5.99, p = .02, \text{partial } \eta^2 = .16$], see Figure 8.

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 they 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 [$F(1,45) = 17.32, p < .001, \text{partial } \eta^2 = .28$], and sensitivity [$F(1,45) = 15.69, p < .001, \text{partial } \eta^2 = .26$], but not for errors [$F(1,45) = 2.4, p = .13, \text{partial } \eta^2 = .05$]. 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 [$F(1,45) = 78.43, p < .001, \text{partial } \eta^2 = .64$], errors [$F(1,45) = 30.09, p < .001, \text{partial } \eta^2 = .40$], and sensitivity [$F(1,45) = 32.08, p < .001, \text{partial } \eta^2 = .42$]. 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 $\eta^2 = .07$], or for errors [$F(2,45) = .05, p = .2$, partial $\eta^2 = .04$], though it was for sensitivity [$F(1,45) = 9.96, p = .003$, partial $\eta^2 = .18$]. 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 [$F(2,45) = .26, p = .77$, partial $\eta^2 = .012$], or for errors [$F(2,45) = .21, p = .81$, partial $\eta^2 = .01$], or for sensitivity [$F(2,45) = 0.10, p = .90$, partial $\eta^2 = .00$], see Figure 10.

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 [$F(1,31) = 90.67, p < .001, \text{partial } \eta^2 = .75$], errors [$F(1,31) = 52.01, p < .001, \text{partial } \eta^2 = .63$], and sensitivity [$F(1,31) = 78.27, p < .001, \text{partial } \eta^2 = .72$]. 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 [$F(1,31) = 51.97, p < .001, \text{partial } \eta^2 = .63$], errors [$F(1,31) = 48.56, p < .001, \text{partial } \eta^2 = .61$], and sensitivity [$F(1,31) = 7.84, p = .009, \text{partial } \eta^2 = .20$]. 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 [$F(1,31) = 9.42, p = .004, \text{partial } \eta^2 = .23$], and sensitivity [$F(1,31) = 7.19, p = .01, \text{partial } \eta^2 = .19$], but not for errors [$F(1,31) = 0.73, p = .40, \text{partial } \eta^2 = .02$]. 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 in Experiment 4.

Next, the interactions are reported. The interaction of regularity-type x objectness was significant for RT [$F(1,31) = 91.66, p < .001, \text{partial } \eta^2 = .75$], errors [$F(1,31) = 32.25, p < .001, \text{partial } \eta^2 = .51$], and sensitivity [$F(1,31) = 21.55, p < .001, \text{partial } \eta^2 = .41$]. 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 [$F(1,31) = 2.48, p = .125, \text{partial } \eta^2 = .07$], or errors [$F(1,31) = .40, p = .53, \text{partial } \eta^2 = .01$], but it was for sensitivity [$F(1,31) = 4.95, p = .03, \text{partial } \eta^2 = .14$]. 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 $\eta^2 = .02$], but it was for errors [$F(1,31) = 11.34$, $p = .002$, partial $\eta^2 = .27$], and for sensitivity [$F(1,31) = 8.39$, $p = .007$, partial $\eta^2 = .21$], see Figure 12.

Chapter 4

4 Effects of line separation and exploration on the visual and haptic detection of symmetry and repetition

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4.1 Abstract

Detecting regularities, like symmetry and repetition, can be used to investigate object and shape perception. Symmetry and nearby lines may both signal that one object is present, so moving lines apart may disrupt symmetry detection, whilst repetition may signal that multiple objects are present. Participants discriminated symmetrical/irregular and repeated/irregular pairs of lines. For vision, as predicted, increased line-separation disrupted symmetry detection more than repetition detection. For haptics, symmetry and repetition detection were similarly disrupted by increased line-separation; also, symmetry was easier to detect than repetition for one-handed exploration and for body midline-aligned stimuli, whereas symmetry was harder to detect than repetition with two-handed exploration of stimuli oriented across the body. These effects of exploration and stimulus orientation show the influence of modality-specific processing rather than properties of the external world on regularity detection. These processes may, in turn, provide insights into the nature of objectness in vision and in touch.

4.2 Introduction

Regularities provide an important cue to the shape and structure of objects in our external world. Most research on regularities has focussed on bilateral mirror-reflection (henceforth termed symmetry). Symmetry is a property of many objects, including our own bodies and those of most animals, fruit, plants and manmade objects such as tools (for reviews, see Treder, 2010; Tyler, 1995; Wagemans, 1995, 1997). Symmetry aids perceptual grouping, for example, by acting as a cue for figure-ground segregation (Machilsen, Pauwels, & Wagemans, 2009). Symmetry is usually easier to detect than other regularities such as repeated lines which have been translated (henceforth termed repetition) or rotational symmetry (Julesz, 1971).

It has been proposed that the presence of different types of regularity may be used to signal different properties in the world (Koning & Wagemans, 2009; Treder & van der Helm, 2007; van der Helm & Treder, 2009). Of particular relevance for the present paper is whether symmetry may signal the presence of a single, bilaterally symmetric object, whilst repetition signals the presence of multiple, similarly shaped objects. This hypothesis has been supported by a number of studies which have reported an interaction between objectness and regularity-type (e.g., Baylis & Driver, 1995; Bertamini, Friedenbergl & Kubovy, 1997; Bertamini, 2010; Lawson & Cecchetto, 2015). These authors found that symmetry was easier to detect for one-object stimuli with two regular sides than for two-objects stimuli where the facing sides of the two objects were regular. In contrast, repetition was easier to detect for two-objects stimuli than one-object stimuli.

Koning and Wagemans (2009) suggested that this interaction between objectness and regularity-type might reflect the basic strategies which vision uses to extract information, rather than high-level, cognitive strategies such as mental translations. To test their account, they again used pairs of edges belonging to either a single object or two objects. However, unlike previous studies which used 2D shapes their stimuli appeared to be planar, 3D objects tilted in depth by 45°. The use of these projected 3D objects to test regularity detection minimised figure-ground ambiguity and prevented the use of matching strategies involving simple mental translations. Despite these

changes, Koning and Wagemans (2009) found an interaction between objectness and regularity-type, replicating previous results. They therefore concluded that structural differences between stimuli, and not the use of high-level matching strategies, underlay the one-object advantage for symmetry and the two-objects advantage for repetition.

However, all of the studies reviewed above tested vision only. Recently, Lawson and Cecchetto (2015) tested whether Koning and Wagemans' (2009) conclusion generalised to regularity detection in a different modality, namely haptics (our sense of active touch). Haptics is the only other modality which is specialised at extracting shape information and there are many similarities in how vision and haptics identify objects. Across a number of studies, we have compared the ability of vision and haptics to do the same tasks using the same stimuli in order to examine whether effects found for visual processing generalise to haptics (e.g., Collier & Lawson, submitted; Craddock & Lawson, 2009a; Lawson, 2009; Martinovic, Lawson & Craddock, 2012). In the present study, we extended our approach to test regularity detection for symmetry and repetition. It is well established that haptics can detect symmetry (see Cattaneo et al., 2014, for a recent review) but, as far as we are aware, no other studies have investigated the haptic detection of repetition.

Lawson and Cecchetto (2015) found that there was an important difference between visual and haptic regularity detection. For vision, we found a one-object advantage for detecting symmetry and a two-objects advantage for detecting repetition, replicating the interaction reported by Koning and Wagemans (2009) and others. However, for haptics, there was a one-object advantage for both symmetry and repetition detection. These results suggest that effects on regularity detection may not be informing us about properties of the external world. Instead they may be telling us about differences in processing across our sensory systems. This alternative account was examined in the present study. However, in the present studies, unlike most previous studies including Lawson and Cecchetto (2015), we did not use planar, closed-contour shapes. As we now explain, this was due to a concern raised by van der Helm and Treder (2009).

Regularities belonging to objects

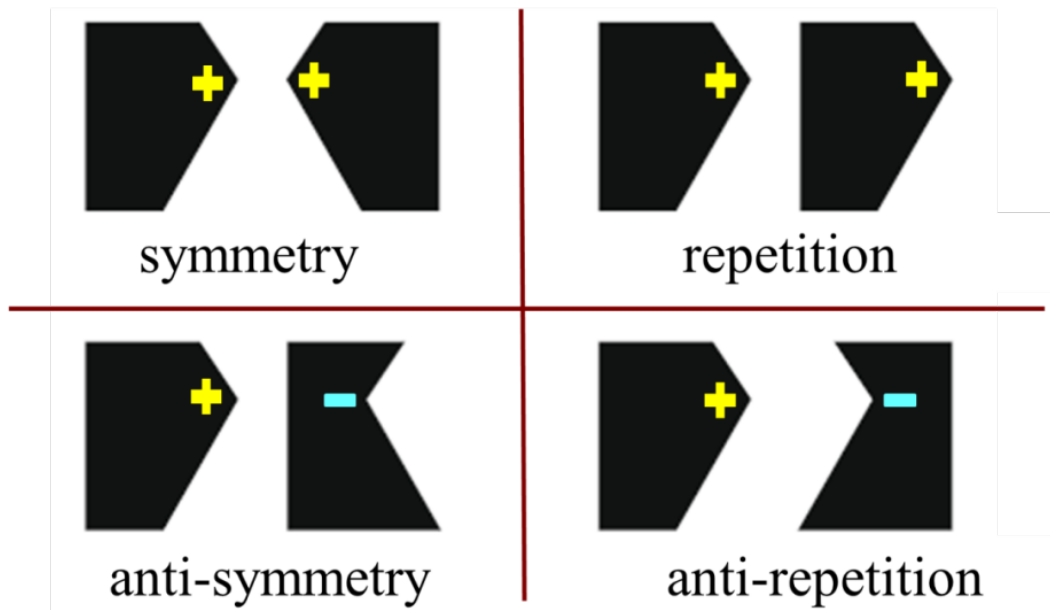


Figure 1. An illustration of four types of regular, two-objects, planar shapes varying in regularity-type (symmetry versus repetition) and regularity-polarity (truly regular versus anti-regular) based on Figure 1 of van der Helm and Treder (2009). For anti-repetition and anti-symmetry stimuli, the two task-critical, regular contours have opposite polarities in terms of convexity (+) and concavity (-), defined with respect to the closed-contour object, and in terms of colour and luminance of the object, defined relative to its background. Baylis and Driver (1995), Bertamini et al., (1997), Bertamini (2010), Koning and Wagemans (2009) and Lawson and Cecchetto (2015) all used two-objects stimuli with the task-critical contours on facing sides of the two objects. This meant that these task-critical contours had true symmetry (the inner two lines in the top left case here) but anti-repetition (the inner two lines in the bottom right case here).

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, see Figure 1. True regularities occur if two contours have the same polarities whereas anti-regularities occur if they have opposite polarities, for example with respect to curvature (so mismatched concavities and convexities), colour or luminance. Van der Helm

and Treder's (2009) findings indicated that the visual system treats anti-regularities differently to regularities. All of the studies discussed so far tested anti-repetition (Baylis & Driver, 1995; Bertamini et al., 1997; Bertamini, 2010; Koning & Wagemans, 2009; Lawson & Cecchetto, 2015). Van der Helm and Treder therefore argued that none of these studies actually tested whether repetition detection was easier for two-objects compared to one-object stimuli. They did, though, note that both Corballis and Roldan (1974) and Treder and van der Helm (2007) investigated this issue.

Corballis and Roldan (1974) asked people to compare dots in two 3×2 arrays. The two arrays were either adjacent (so they could be perceived as a single whole) or separated by a gap (so they may have appeared as two, separate objects). The dot patterns were either symmetrical or repeated so all the stimuli were regular and, unusually, the task was to discriminate symmetry from repetition. Symmetry was detected faster for adjacent compared to separated arrays, though this difference was not tested statistically. There was also a trend in the opposite direction for repetition detection (though it was probably not significant), so for an advantage for the separated arrays.

Treder and van der Helm (2007) used stereoscopic depth to assign the two halves of symmetrical and repeated dot patterns to either the same or to two different depth planes. They took advantage of the fact that location in depth influences the grouping of parts with nearby parts being more likely to be perceived as belonging to the same object. Splitting the stimuli across different depth planes disrupted symmetry detection but had little effect on repetition detection, so only symmetry processing clearly benefitted from structural correspondences occurring within a depth plane.

To summarise, van der Helm and Treder (2009) argued that only two studies have investigated the interaction between regularity-type and objectness: Corballis and Roldan (1974) and Treder and van der Helm (2007). However, in both of these studies the interaction (symmetry detection being easier for one-object compared to two-objects stimuli, and vice versa for repetition detection) was found only for dot stimuli, and in neither study was there a clear two-objects advantage for repetition. In addition, Corballis and Roldan (1974) tested regularity discrimination rather than regularity detection, and they did not statistically test whether there was a one-object

advantage for symmetry, or whether there was a two-objects advantage for repetition. Thus, there is still a dearth of evidence as to whether true repetition (as opposed to anti-repetition) is easier to detect visually for two-objects stimuli relative to one-object stimuli and this has never been tested for haptics.

This issue is of wider importance because it may provide insights into what defines an object in vision and touch. The concept of objectness is central to many aspects of spatial and conceptual organisation in both perception and cognition. However, it has proven difficult to define what constitutes an object (Feldman, 2003). Researchers claiming to manipulate objectness often make little attempt to justify their choice of stimuli. The present study aims to introduce an approach which allows us to identify and to compare potential cues to objectness in both vision and touch. We do not assume that objectness is an all or nothing property of a stimulus and we think that multiple cues combine to determine whether a given stimulus is perceived as an object. We are not aware of any previous research that has tried to define what it means to be a haptic object. Our approach is therefore preliminary and we will not claim to provide conclusive evidence about the nature of objectness in haptics. Nevertheless, this topic is an important one which has been neglected for too long, and we think that progress can be made in trying to understand objectness across different modalities.

The present study tested a novel prediction based on previous research suggesting that symmetry detection is easier for one-object stimuli whilst repetition detection is easier for two-objects stimuli. We hypothesised that, on average, closer lines are more likely to be perceived as belonging to the same object and more distant lines as belonging to two different objects (see also Corballis & Roldan, 1974; Treder & van der Helm, 2007). This hypothesis leads to the prediction that it should be easier to detect symmetry when lines are closer because both cues (line separation and the type of regularity) indicate that one object is present. Conversely, repetition should be harder to detect when lines are closer because one cue (line separation) indicates that one object is present whereas the other cue (the type of regularity occurring - here, repetition) indicates that multiple objects are present. We investigated these predictions by testing whether effects of the type of regularity being detected (symmetry versus repetition) interacted with line separation. This approach is

conceptually similar to that taken by Treder and van der Helm (2007). They varied regularity-type (symmetry versus repetition) and stereoscopic depth (the two stimulus halves were on the same versus on different depth planes) to investigate how regularity detection was influenced by whether these cues provided consistent or conflicting interpretations of objectness. To avoid the issues discussed above arising from using anti-regularities (see van der Helm & Treder, 2009), and to simplify the stimuli, the experiments reported here presented only lines rather than planar shapes (see Figure 2).

In summary, in the three studies reported here we contrasted how potential cues to objectness, such as the spatial separation between two lines, influenced the detection of symmetry and repetition. As in Lawson and Cecchetto (2015), we used matched stimuli and tasks to compare regularity detection for vision (Experiment 1) and for haptics (Experiments 2 and 3). The goal of this research was to investigate whether there is a one-object advantage (cued by a small line separation) for symmetry detection and a two-objects advantage (cued by a large line separation) for detecting true repetition, and whether any such effects found for regularity detection reflect modality-specific processing, or if they reveal differences arising directly from the presence of regularities out in the physical world.

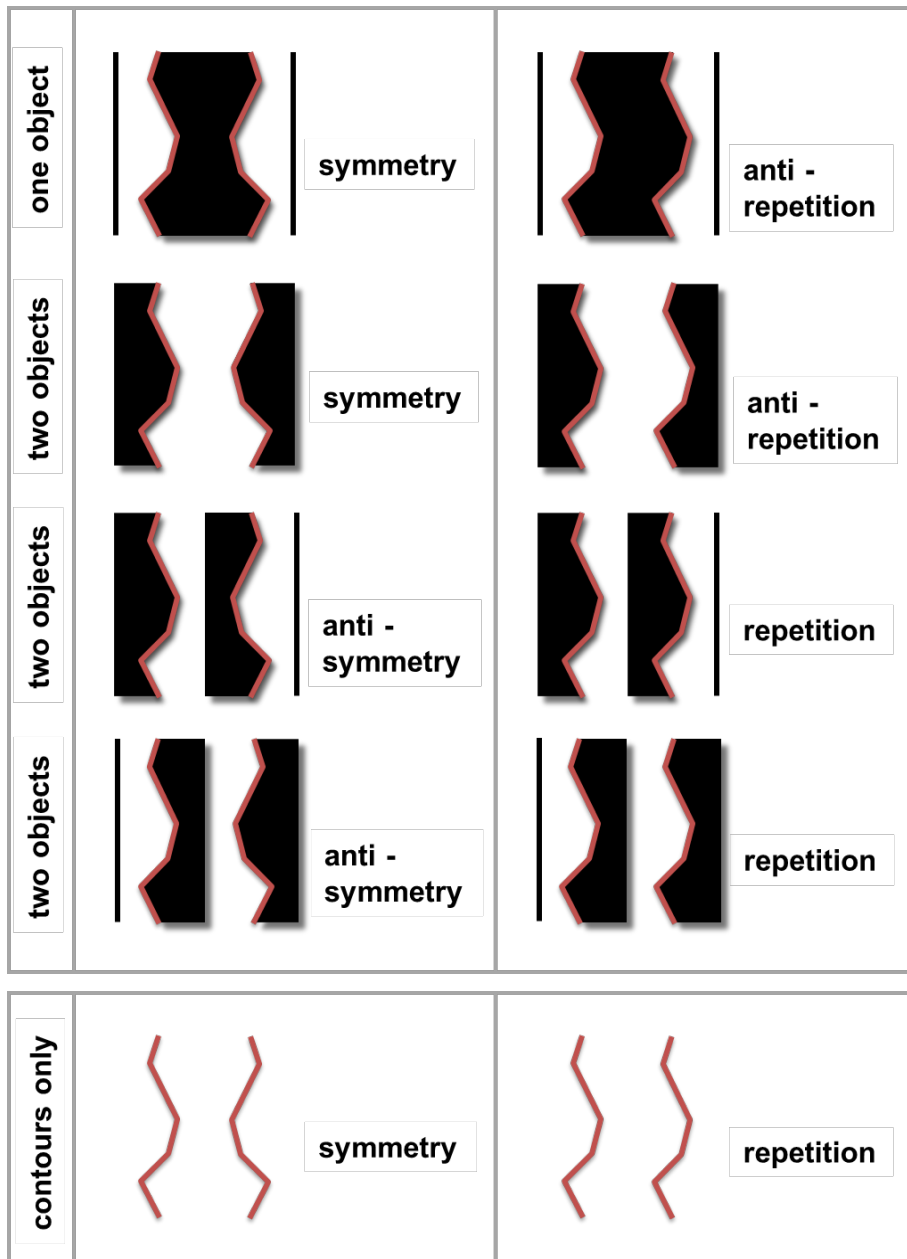


Figure 2. The upper box illustrates the type of planar, 2D stimuli that have previously been used to test the interaction between regularity-type (symmetry versus repetition) and objectness (one versus two). The pairs of task-critical, regular lines are highlighted here but they were not shown to participants. Baylis and Driver (1995), Bertamini et al., (1997), Bertamini (2010), Koning and Wagemans (2009) and Lawson and Cecchetto (2015) presented stimuli like those in the top two rows of the upper box (so true symmetry and anti-repetition stimuli); they did not show any true repetition or anti-symmetry stimuli. The lower box illustrates the line-only stimuli used in the present studies. Note that the task-critical, symmetrical and repeated lines for all four rows of planar stimuli shown in the upper box are identical to these lines.

4.3 Experiment 1

In Experiment 1 participants saw pairs of vertically aligned, 2D lines. We investigated whether people found it harder to visually detect regularities (either symmetry or repetition, in separate blocks) when the horizontal separation between the two lines increased from 25mm up to 50mm and to 100mm. We expected that smaller separations would make it more likely that the lines were perceived as belonging to a single object, whereas larger separations were more likely to be perceived as belonging to two different objects. We also hypothesised that symmetry is used as a cue for the presence of a single object, whereas repetition provides evidence for the presence of multiple objects. We therefore predicted that symmetry detection should be easier for small relative to large line separations. Here, nearby pairs of symmetrical lines provide consistent cues that a single object is present whereas distant pairs of symmetrical lines provide conflicting cues about objectness. The opposite pattern was predicted for repetition. Here, well-separated pairs of repeated lines provide consistent evidence for the presence of two objects, whilst nearby, repeated lines provide conflicting cues about objectness. However, there are independent reasons why regularity detection may be harder at large line separations, such as the difficulty of visually perceiving more peripheral stimuli. Any such effects would counter the expected large-separation advantage for repetition (whilst enhancing the predicted large-separation cost for symmetry). We therefore simply predicted that increasing line separation would disrupt symmetry detection more than repetition detection.

4.3.1 Method

4.3.1.1 *Participants*

Twenty-four students from the University of Liverpool (16 females, mean age = 20 years, s.d. = 2.8, range 18-31) volunteered to take part in the experiment. In all of the experiments reported in this paper the participants had normal or corrected-to-normal vision, they self-reported as right-handed, they had no known conditions affecting their sense of touch and most received

course credits in exchange for their time. All the experiments received ethical approval from the local ethics committee.

4.3.1.2 *Materials*

We produced a set of 480 pairs of lines based on the 40 unique lines used in Experiment 1 of Lawson and Cecchetto (2015). However, the vertices of these unique lines were rounded to ensure that when the lines were felt (in Experiments 2 and 3) there would be no sharp corners which might be difficult to explore by touch. Each unique line had four vertices with the top and bottom of each line vertically aligned, see Figure 3. Each unique line was paired with a mirror-reflected version of itself, with the same version of itself, with a mirror-reflected version of a different unique line and, finally, with a repeated version of a different unique line. This produced the symmetrical, repeated and two irregular stimuli respectively. For the irregular stimuli, unique line 17 could be paired with unique line 3 for its two irregular stimuli, whilst unique line 3 could be paired with unique line 8, and so on. There were 480 trials in total (40 unique lines × regular/irregular stimuli × symmetry/repetition × regularity-type × small/medium/large line separations).

Pairs of lines were presented as 2D images on a computer monitor and were viewed from a distance of approximately 50cm. The LCD widescreen monitor was 58cm diagonally and had a resolution of 1280 × 1024 pixels. Each line was 3mm wide and 100mm high. The top and bottom of each line was positioned 12.5mm each side of the midpoint of the monitor for the 25mm separated lines, 25mm each side of it for the 50mm separated lines, and 50mm each side of it for the 100mm separated lines. The 100mm separated lines subtended around 11° × 11°.

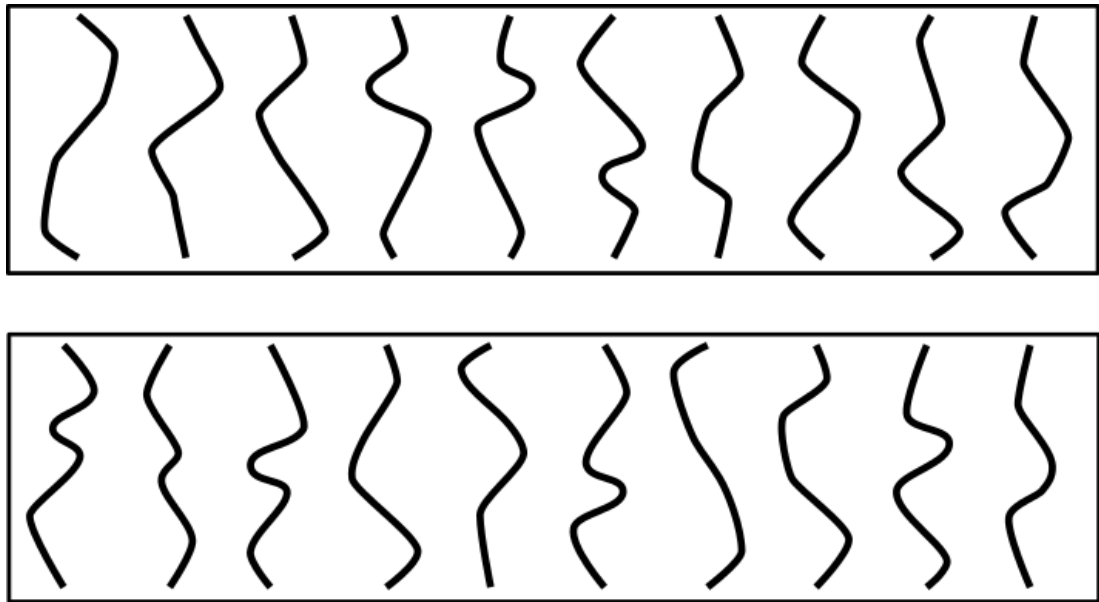


Figure 3. The 20 unique lines used to generate the regular stimuli for Experiments 1, 2 and 3. In Experiment 1 only, 20 additional unique lines were used which were produced in a similar way. The unique lines are shown here ordered from easiest (top left) to hardest (bottom right) in terms of accuracy in previous regularity detection tasks (discriminating symmetrical from irregular stimuli and repeated from irregular stimuli in Experiment 1 of Lawson & Cecchetto, 2015).

4.3.1.3 Design

All participants did one block of symmetry detection and one block of repetition detection, with block order counterbalanced across participants. Each block had 240 trials (40 unique lines x regular/irregular stimuli x small/medium/large line separations). These trials were presented in a different, random order for each participant.

4.3.1.4 Procedure

Participants sat in a normally lit room. Participants were instructed to centre their body midline to the centre of the computer monitor. Before starting each block, participants were told about the nature of the regularity they were about to detect, its orientation, and that the stimuli could have different line separations. Each block of experimental trials was preceded by 10 practice trials taken from that block. These practice trials were the same for

all participants and they included five regular and five irregular trials and a mix of the three line separations. At the start of each trial, a central fixation cross appeared on the monitor for 1s. This was replaced by the stimulus which remained on the monitor until the participant responded. Visual prompts about how to respond were presented on the monitor whenever the stimulus was visible, see Figure 4. Participants responded using the computer keyboard, pressing "s" for regular trials and "k" for irregular trials as quickly and as accurately as possible. Reaction times (RT) were recorded from stimulus onset until the participant responded. The experiment took around 30 minutes to complete.

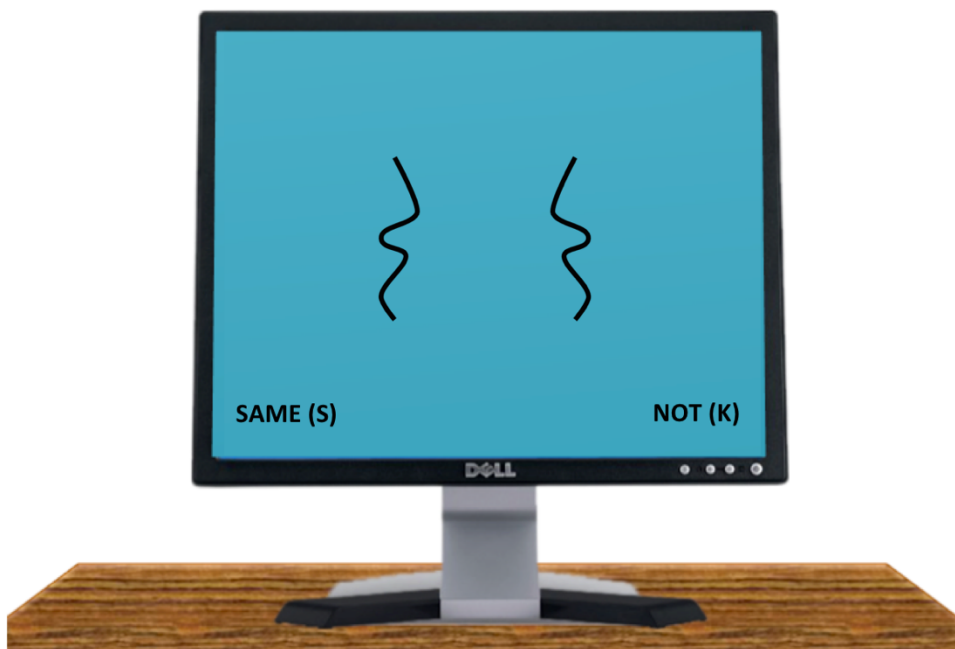


Figure 4. An example of a large line separation, symmetrical stimulus presented visually on the computer monitor in Experiment 1.

4.3.2 Results

Correct RT faster than 0.4s or slower than 3.5s were removed as outliers (less than 2% of trials). To be consistent with reporting in previous studies, ANOVAs were conducted on the mean correct RT and on the percentage of errors for regular trials only (also performance on irregular trials is difficult to interpret theoretically). In all three experiments reported here, we also

analysed measures of sensitivity (d') and bias (c') which included data from irregular trials, see Appendix. There were two within-participants factors in the ANOVAs: regularity-type (symmetry or repetition) and line separation (small, medium or large).

Regularity-type was significant for RT [$F(1,23) = 19.71, p < .001, \text{partial } \eta^2 = .46$] but not for errors [$F(1,23) = 0.01, p = .9, \text{partial } \eta^2 = .00$]. Symmetry detection (0.93s, 6% errors) was faster but not more accurate than repetition detection (1.09s, 6%).

Line separation was significant for both RT [$F(2,46) = 135.04, p < .001, \text{partial } \eta^2 = .85$] and errors [$F(2,46) = 29.19, p < .001, \text{partial } \eta^2 = .56$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that regularity detection was both faster and more accurate with small separations (0.89s, 3% errors) than with medium separations (1.01s, 6%) and, in turn, that detection was both faster and more accurate with medium separations compared to large separations (1.13s, 9%).

Finally, the interaction of regularity-type \times line separation was significant for both RT [$F(2,46) = 12.32, p < .001, \text{partial } \eta^2 = .35$] and errors [$F(2,46) = 11.59, p < .001, \text{partial } \eta^2 = .34$], see Figure 5. To understand this interaction, we calculated the difference between regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This revealed that increased line separation (100mm - 25mm) was significantly more disruptive for detecting symmetry (0.28s, 10% errors) than for detecting repetition (0.19s, 2%) for both RT [$F(1,23) = 6.74, p = .016, \text{partial } \eta^2 = .28$] and errors [$F(1,23) = 12.62, p = .002, \text{partial } \eta^2 = .35$].

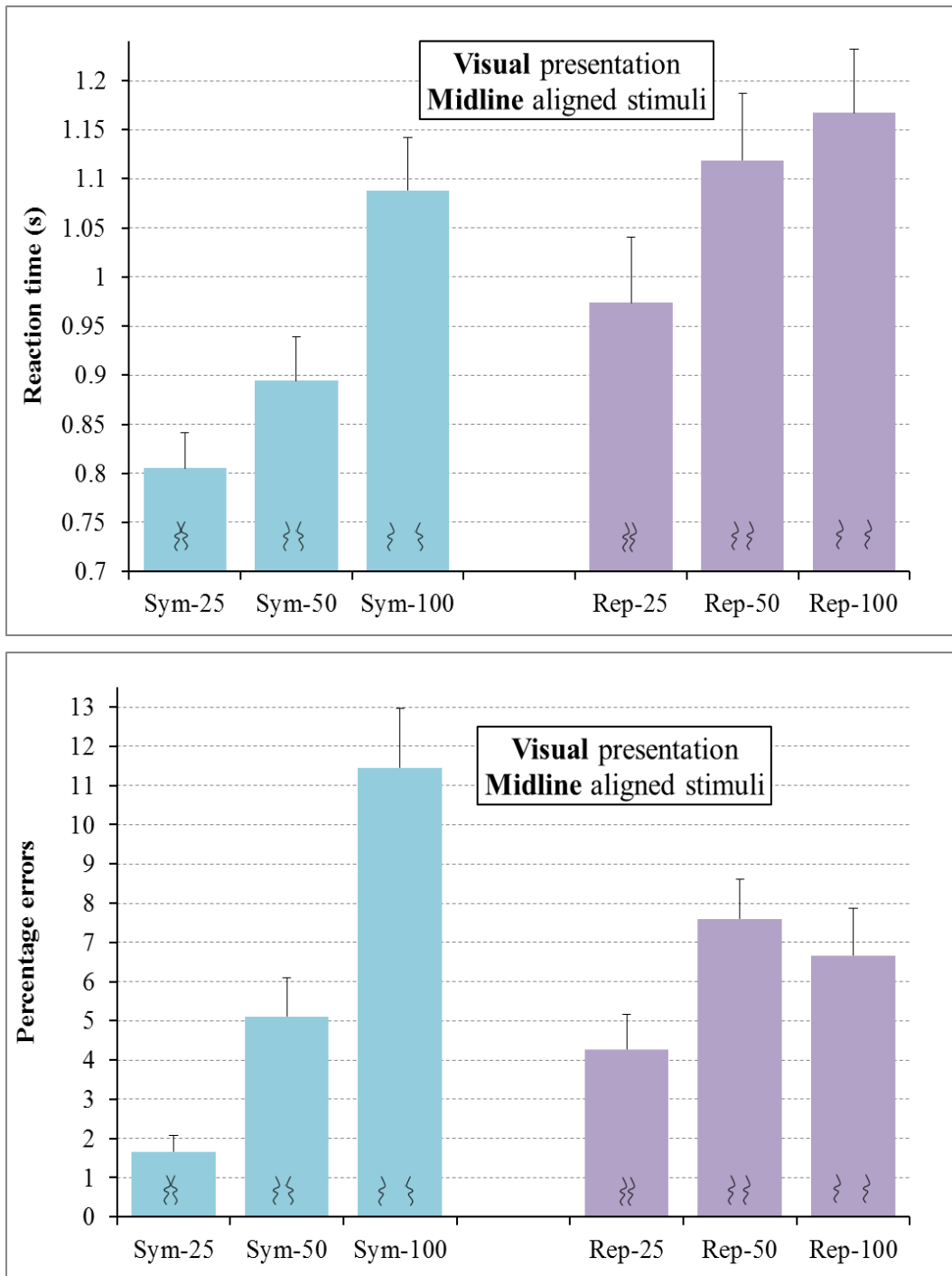


Figure 5. Results for regular trials for Experiment 1 for the visual detection of symmetry (Sym) and repetition (Rep) for line separations of 25mm, 50mm and 100mm for RT (top) and errors (bottom). Error bars represent one standard error of the mean. In this, and the remaining figures showing experimental results, the icons at the base of each bar schematically represent the type of stimuli in that condition: symmetrical or repeated with small, medium or large separations between each pair of lines.

4.3.3 Discussion

In Experiment 1, our hypothesis was that line separation and regularity-type are both factors which provide evidence about objectness. We therefore predicted that effects of line separation should interact with those of regularity-type, with the disruptive effect of increased line separation being greater for symmetry detection than for repetition detection. Our results for visual regularity detection confirmed this prediction. Converging evidence for this interaction between the effects of objectness and regularity-type on vision has been reported when objectness is manipulated using planar shapes like those shown in Figure 1 (Baylis & Driver, 1995; Bertamini et al., 1997; Bertamini, 2010; Koning & Wagemans, 2009; Lawson & Cecchetto, 2015). Further discussion of these results for vision is deferred until we have described the results of Experiments 2 and 3, which investigated the interaction between regularity-type and line separation for haptic regularity detection.

4.4 Experiment 2

Experiment 2 largely replicated Experiment 1, except that the stimuli were presented haptically, as 3D raised lines, rather than visually, as 2D digital images. We again investigated the effects of type of regularity (symmetry or repetition) and line separation on regularity detection. Based on the results of Experiment 1, we might expect that symmetry should be easier to detect with small line separations, since nearby lines and symmetry may provide consistent evidence that a single object is present, whereas large line separations and symmetry provide conflicting cues about objectness. The opposite pattern might be expected for repetition, with repetition being easier to detect at large line separations, since repetition and distant lines may provide consistent cues that two objects are present. Note, though, that there are independent reasons why regularities might become harder to detect at large line separations (irrespective of whether symmetry or repetition is being detected). For example, participants probably find it harder to align their fingers precisely in space when they are further apart. From debriefing and informal observation, we believe that finger alignment is critical for haptic regularity detection. Any such independent effects would counter the

expected advantage for large line separations for repetition (whilst enhancing the cost for large line separations for symmetry). We therefore simply predicted that, if haptic regularity detection behaves like visual regularity detection, then increased line separation should disrupt symmetry detection more than repetition detection.

However, importantly, when we manipulated perceived objectness in previous experiments using closed-contour, planar stimuli rather than line separation (Lawson & Cecchetto, 2015; see Figure 2), we obtained an interaction between objectness and regularity-type for vision but not for haptics. Based on these findings, if haptics again behaves differently to vision, in Experiment 2 compared to Experiment 1, we would not predict a greater influence of line separation when haptically detecting symmetry compared to repetition.

4.4.1 Method

4.4.1.1 Participants

The same 24 participants from Experiment 1 took part in Experiment 2, in a second, separate session. This haptic session was always conducted before visual testing occurred in Experiment 1 (on average, 6 days earlier, range 0-15 days). However, for ease of explanation, we described the visual experiment first.

4.4.1.2 Materials

There were 240 stimuli, comprising half of the 480 pairs of lines used in Experiment 1. The pairs of lines were based on 20 of the 40 unique lines used in Experiment 1. These 20 lines were selected to span the range of difficulty that we observed in Experiment 1 of Lawson and Cecchetto (2015), which used the same lines, see Figure 3. This was done by ordering performance for regularity detection for each line from best to worst and then selecting alternate lines.

We used a laser cutter to produce the 3mm wide x 100mm tall plastic lines from 5mm thick acrylic sheets. Pairs of lines were glued onto 15cm wide x 10cm tall cardboard bases with the top and bottom of each line aligned with the top and bottom of the base respectively, so the long axes of each line lay parallel to each other. The dimensions of the stimuli were matched to the dimensions of the stimuli used in Experiment 1 so the top and bottom of each line was positioned 12.5mm each side of the midpoint of the base for the 25mm separated lines, 25mm each side of it for the 50mm separated lines and 50mm each side of it for the 100mm separated lines.

4.4.1.3 Line separation discrimination check

We conducted a rating study to check that participants in Experiment 2 could haptically discriminate between the line separations presented. Twenty-four students from the University of Liverpool (17 females, mean age = 19 years, s.d. = 1.5, range 18-25) volunteered to take part. Twelve participants were allocated to the two-handed exploration group. They felt two lines simultaneously with their two index fingers. The remaining 12 participants were allocated to the one-handed exploration group. They used their right index finger to feel the right line and their right thumb to feel the left line. This rating study used the same procedure and a subset of the trials used in Experiment 2. Each participant completed the same nine trials which were presented in a fixed, pseudorandom order. These comprised three symmetry trials, three repetition trials and three irregular trials, each with a small, medium and large line separation. Participants responded verbally as to, first, whether each pair of lines were symmetrical, repeated or irregular, and then whether each pair of lines was separated by a small, medium or large gap. Thus, both tasks involved distinguishing between three categories. Accuracy was similar for the regularity discrimination task (21% errors with one hand, 27% with two hands) and the line separation discrimination task (23% errors with one hand, 21% with two hands).

4.4.1.4 *Design*

This was identical to Experiment 1 except for the following points. Participants did the same block order (symmetry detection then repetition detection or vice versa) as they had done in Experiment 1. However, because regularity detection is much faster for vision than for haptics, and because there were only half the stimuli in Experiment 2 as in Experiment 1, participants only did a quarter of the number of trials in Experiment 2 as in Experiment 1. Participants thus completed 120 of the possible 240 experimental trials in two blocks of 60 trials. The 240 trials (20 unique lines x regular/irregular stimuli x small/medium/large line separations) were divided into four blocks of 60 trials. Each of these blocks included 20 stimuli at each of the three line separations and they also all included three stimuli based on each of the 20 unique lines with half the stimuli being regular and half irregular in each block. Trials within a block were presented in a fixed, pseudorandom order. The assignment of participants to blocks was counterbalanced by dividing the participants into six subgroups of four participants and then, within each subgroup, all four blocks were completed once as the first block and once as the second block.

4.4.1.5 *Procedure*

This was identical to Experiment 1 except for the following points. Stimuli were presented in front of participants on a 70cm high table, see Figure 6. A curtain hung directly in front of the participant, around 15cm inside the edge of the table. Participants put their hands under the curtain, hiding both the stimuli and their hands from view. On the table in front of the curtain there were two labels, "same" on the left and "different" on the right, to remind participants which foot-pedal they should use to respond on regular and irregular trials respectively. Participants were instructed to centre their body midline with the midpoint of the two response labels and the midpoint of the two foot pedals.

The experimenter placed stimuli, one at a time, in a recess (15cm wide x 10cm tall) within a 45cm wide x 30cm tall foamboard frame. The frame

ensured that the stimuli were presented at a fixed position and orientation. The centre of the recess was in line with the participant's body midline and was 25cm from the edge of the table and approximately 40cm from the participant. There was a soft patch on the frame, positioned above the middle of the top of the recess, see Figure 6. Participants rested both of their index fingers on this startpoint patch before beginning each trial, so they started exploring lines from the top.

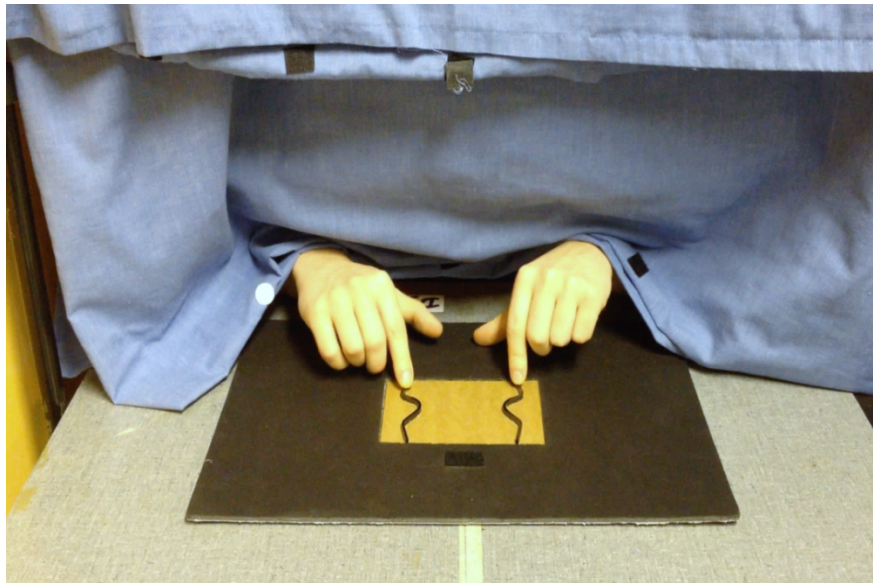


Figure 6. Haptic exploration of a large line separation (100 mm), symmetrical stimulus in Experiment 2 as seen from the experimenter's perspective. Note the startpoint patch at the top of the stimulus.

Before starting the experiment, participants were shown visually four practice stimuli. These stimuli were similar to the experimental stimuli: two were regular, two were irregular, and all had a medium separation. Participants then did four practice trials haptically using these stimuli. They were instructed to feel one line with each of their two index fingers, and to decide whether the lines were regular.

At the start of each trial the experimenter placed a stimulus in the recess, then triggered an audible "go now" signal using the computer. This indicated to the participant that they should move their fingers from the resting position on the startpoint patch, to begin to explore the two lines. Participants were told to respond as quickly and as accurately as possible by pressing a foot pedal. Reaction times (RT) were measured from the offset of

the go signal to the participant's pedal response. Following their response, a high or a low pitch feedback sound was emitted to indicate a correct or a wrong answer respectively.

After the first block of 60 experimental trials, participants were instructed about the new regularity that they would have to detect. They were again shown visually four new practice stimuli which were then used in four haptic practice trials before they did the second block of 60 experimental trials. The experiment took around one hour to complete. Afterwards the experimenter checked to ensure that the participant had not seen any of the stimuli.

4.4.2 Results

No participant was replaced. Correct RT faster than 1s or slower than 35s were removed as outliers (less than 1% of trials). As in Experiment 1, ANOVAs were conducted on the mean correct RT and on the percentage of errors for regular trials only. Analyses of measures of sensitivity (d') and bias (c') are given in the Appendix. There were two within-participants factors in the ANOVAs: regularity-type (symmetry or repetition) and line separation (small, medium or large).

Regularity-type was significant for both RT [$F(1,23) = 6.86$, $p = .015$, partial $\eta^2 = .23$] and errors [$F(1,23) = 11.77$, $p = .002$, partial $\eta^2 = .34$]. Symmetry detection (7.2s, 8% errors) was both faster and more accurate than repetition detection (8.7s, 16%).

Line separation was significant for RT [$F(2,46) = 3.80$, $p = .03$, partial $\eta^2 = .14$] and was marginally significant for errors [$F(2,46) = 2.97$, $p = .06$, partial $\eta^2 = .11$]. The overall pattern was for regularity to be easiest to detect at small separations (7.6s, 9% errors), inbetween for medium separations (8.0s, 12.5%) and hardest for large separations (8.2s, 15%). However, in post-hoc Newman-Keuls analyses only the difference in speed between small and large separations was significant ($p < .05$).

Finally, the interaction of regularity-type x line separation was not significant for RT [$F(2,46) = 0.50$, $p = .6$, partial $\eta^2 = .02$] or for errors [$F(2,46) =$

0.70, $p = .5$, partial $\eta^2 = .03$]. The effect of line separation was similar for symmetry detection and repetition detection, see Figure 7.

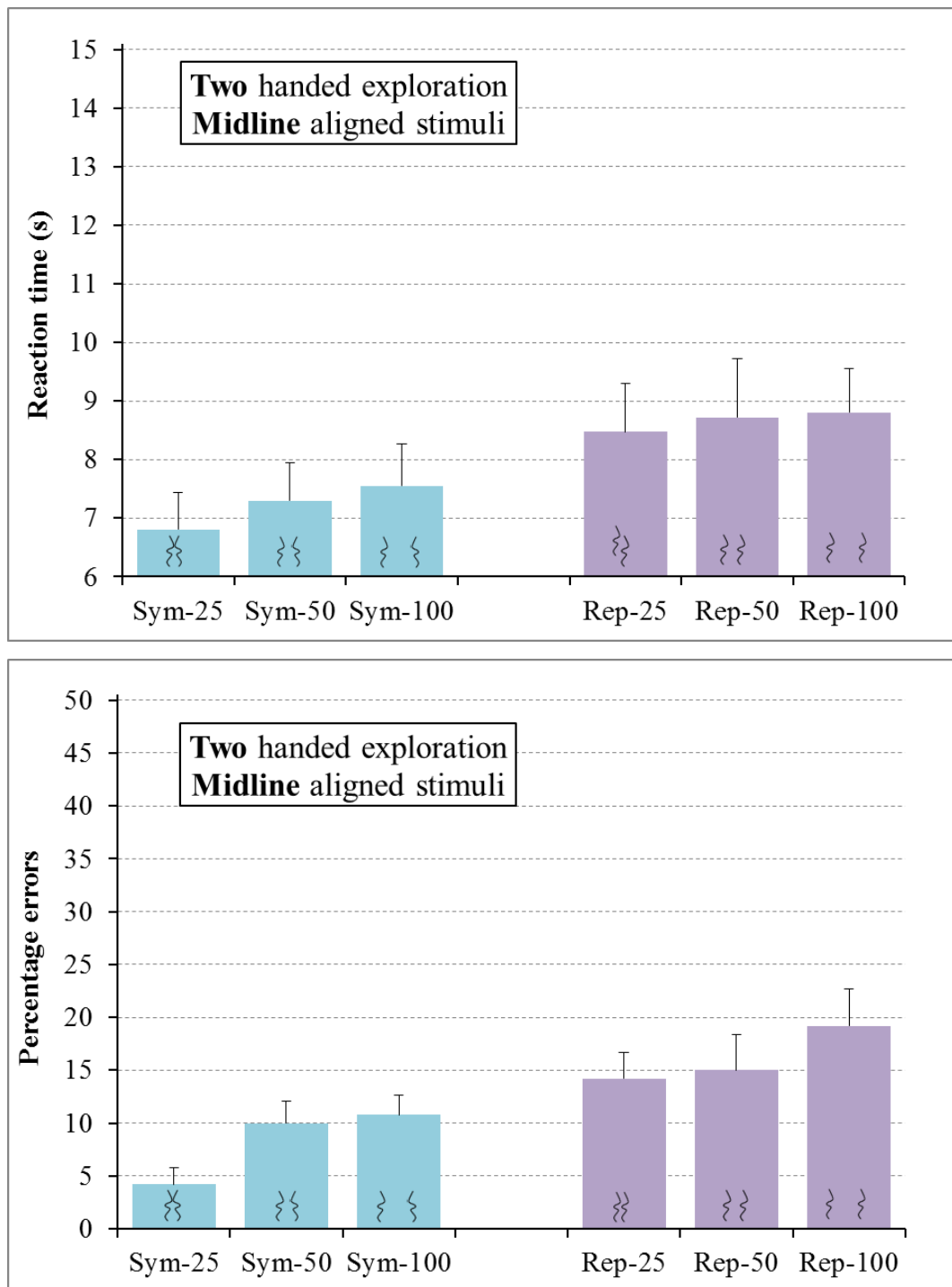


Figure 7. Results for regular trials for Experiment 2 for the haptic detection of symmetry (Sym) and repetition (Rep) for line separations of 25mm, 50mm and 100mm for RT (top) and errors (bottom). Error bars represent one standard error of the mean.

4.4.3 Discussion

Experiment 2 revealed a modest cost of increasing line separation on haptic regularity detection together with an overall advantage for detecting symmetry compared to repetition. Unlike visual regularity detection in Experiment 1, we did not find a greater cost of line separation when detecting symmetry compared to repetition, for either the RT or the error analyses of regular trials. This difference between the results of Experiments 1 and 2 suggests that modality-specific processing influences the detection of regularities. This conclusion is consistent with the findings of Lawson and Cecchetto (2015, poster from Chapter 3) where we compared regularity detection in vision and touch for planar, closed-contour shapes (see Figure 2). However, we should note that the results of the sensitivity analysis revealed an interaction in the predicted direction between the effects of line separation and regularity type, see the Appendix, so there was some inconsistency in the results. Experiment 3 was therefore conducted to investigate this issue further.

4.5 Experiment 3

Experiment 3 was conducted to probe whether effects on regularity detection reflect perceptual processes unique to haptics rather than reflecting properties of the physical stimuli. This question was addressed by, first, changing the orientation of the lines relative to a body-centred spatial frame of reference and, second, altering the manner of haptic exploration. Both of these manipulations were expected to change modality-specific aspects of perceptual processing whilst leaving unaltered the stimuli and their surrounding environment. If an understanding of regularity detection tells us about the information available to us in the world then neither manipulation should affect performance. However, if regularity detection is sensitive to how information is acquired and processed then both manipulations may influence performance. The results for separate pairs of lines in Experiments 1 and 2 here, and for planar, closed-contour shapes in Lawson and Cecchetto (2015), suggest that effects of regularity-type and objectness differ for visual versus haptic regularity detection. This supports the latter prediction.

Experiment 3 replicated Experiment 2 except for two main points. First, the stimuli were rotated by 90° so that the axis of regularity ran perpendicular to the body midline (in the across condition) rather than being aligned with it (as in Experiments 1 and 2). When stimuli are aligned with their body-midline, participants can represent symmetrical stimuli using a highly salient spatial frame of reference based on the symmetry of their own body (e.g., Ballesteros, Millar & Reales, 1998). This led us to predict that, in Experiment 3, having the axis of regularity of symmetrical stimuli aligned with the axis of bilateral symmetry of the participant's own body midline would aid symmetry detection relative to repetition detection. Furthermore, any benefit from using this salient reference frame should be weaker, or absent, if the axis of regularity of symmetrical stimuli was perpendicular to the axis of bilateral symmetry of the participant's own body midline, as it was for across stimuli in Experiment 3. We therefore also predicted that symmetry detection would be harder in the across than the aligned condition in Experiment 3.

Second, in Experiment 3 the manner of stimulus exploration was manipulated between participants. One group used the same, two-handed exploration tested in Experiment 2, with their two index fingers each feeling one of the two lines, see Figure 8. A second group explored stimuli using only one hand. They used their right index finger to explore the top line and their right thumb to explore the bottom line. We reasoned that, in addition to regularity-type and line separation, the manner of exploration could provide a third, independent and modality-specific cue to objectness. In our everyday interactions we often explore and hold a single object in one of our hands. Thus, if we feel two lines with two parts of one hand (here, the thumb and index finger) this may be used as a cue that we are feeling two parts of the same object rather than feeling two different objects. In contrast, we frequently touch and use two different objects with our right and our left hands. Thus, if each of our index fingers feels a different line, this may be used as a cue that we are feeling two different objects. One-object interpretations of line pairs may therefore be more consistent with one-handed exploration than two-handed exploration and vice versa for two-objects interpretations. If so, then symmetry should be easier to detect for one-handed exploration (since here cues from both regularity-type and exploration would consistently indicate that one object was present) compared to two-handed exploration (where cues

about objectness would be conflicting) and vice versa for repetition (which should be easier to detect with two-handed than one-handed exploration).

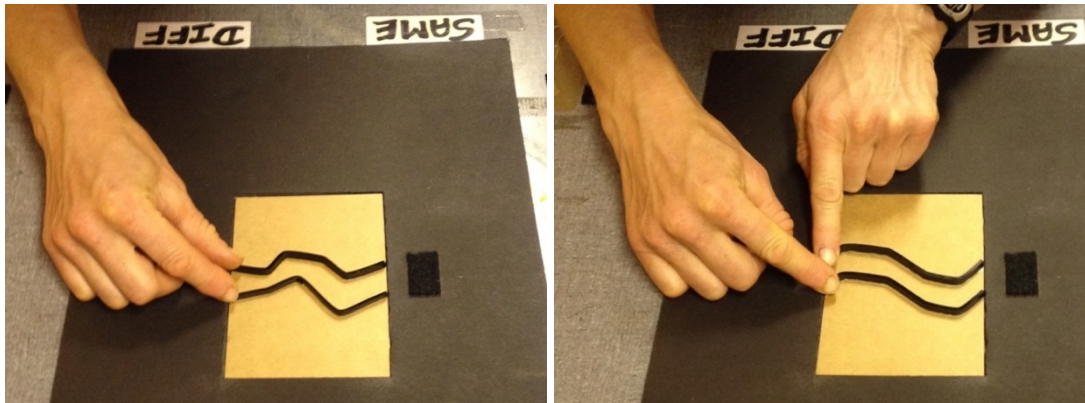


Figure 8. A participant in Experiment 3 shown, on the left, using one hand to explore a pair of irregular lines separated by 25mm and, on the right, using two hands to explore a pair of repeated lines separated by 25mm (right). Note that both stimuli are oriented such that the axis of regularity is perpendicular to the participant's body midline. This contrasts to Experiments 1 and 2 where the stimuli were aligned with the body midline (see Figures 4 and 6). For the purpose of these photographs, the curtain was raised to show the response labels which reminded the participant which foot pedal to use. The black startpoint patch is shown to the right of the stimulus (so it was on the left side for the participant).

4.5.1 Method

The design, stimuli and procedure in Experiment 3 were identical to Experiment 2 except for the following points. Thirty-two students from the University of Liverpool (22 females, mean age = 21 years, s.d. = 3.8, range 18-31) volunteered to take part in the experiment. All of the stimuli were rotated 90° counterclockwise so that the orientation of the regularity was perpendicular to the participant's body midline. The frame that the stimuli were placed in was also rotated 90° counterclockwise so the startpoint patch on which participants rested their fingers at the beginning of each trial was on the left side of the frame rather than on the top of the frame, see Figure 8. Participants started each trial by moving their fingers from left to right rather than from top to bottom. Half of the participants were instructed to explore

the two lines simultaneously with their two index fingers, as in Experiment 2. The remaining participants were instructed to explore the two lines using their right hand only, with their right index finger feeling the top line and their right thumb feeling the bottom line, see Figure 8.

4.5.2 Results

No participant was replaced. There was one empty cell in the RT data for one participant in the one-handed exploration group, which was filled by the mean for that condition. As in Experiment 2, correct RT faster than 1s or slower than 35s were removed as outliers (less than 1% of trials), and ANOVAs were conducted on the mean correct RT and on the percentage of errors for regular trials only. For clarity of presentation, we give the results for the two exploration groups separately below. However, ANOVAs comparing the two groups tested in Experiment 3, and ANOVAs comparing the results of Experiment 2 to the two-handed exploration group in Experiment 3, are given in the Appendix. Analyses of measures of sensitivity (d') and bias (c') for each group are also given in the Appendix.

One-handed exploration group

Participants used the thumb and index finger of their right hand to explore stimuli that were oriented to be perpendicular to their body midline. There were two within-participants factors: regularity-type (symmetry or repetition) and line separation (small, medium or large).

Regularity-type was significant for both RT [$F(1,15) = 6.32$, $p = .02$, partial $\eta^2 = .30$] and errors [$F(1,15) = 5.89$, $p = .03$, partial $\eta^2 = .28$]. We found the advantage for symmetry detection (8.2s, 14% errors) over repetition detection (9.7s, 20%) that we obtained in Experiment 2.

Line separation was significant for both RT [$F(2,30) = 30.54$, $p < .001$, partial $\eta^2 = .67$] and errors [$F(2,30) = 13.54$, $p < .001$, partial $\eta^2 = .47$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that regularity detection was harder for large separations (10.2s, 29% errors) than for small (8.0s, 7.5%) and medium (8.6s, 14%) separations, with no significant difference between small and medium separations.

The interaction of regularity-type \times line separation was not significant for RT [$F(2,30) = 1.30$, $p = .3$, partial $\eta^2 = .08$] but it was for errors [$F(2,30) = 8.52$, $p = .001$, partial $\eta^2 = .36$], see Figure 9. Again, to understand this interaction we calculated the difference between regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This revealed that the cost of increased line separation (100mm - 25mm) on accuracy was significantly less for symmetry (9% errors) than for repetition (34%), [$F(1,15) = 15.96$, $p = .001$, partial $\eta^2 = .51$]. Note that this pattern shows the reverse interaction to that which we found for vision in Experiment 1 where the accuracy of repetition detection was more sensitive to line separation than was symmetry detection.

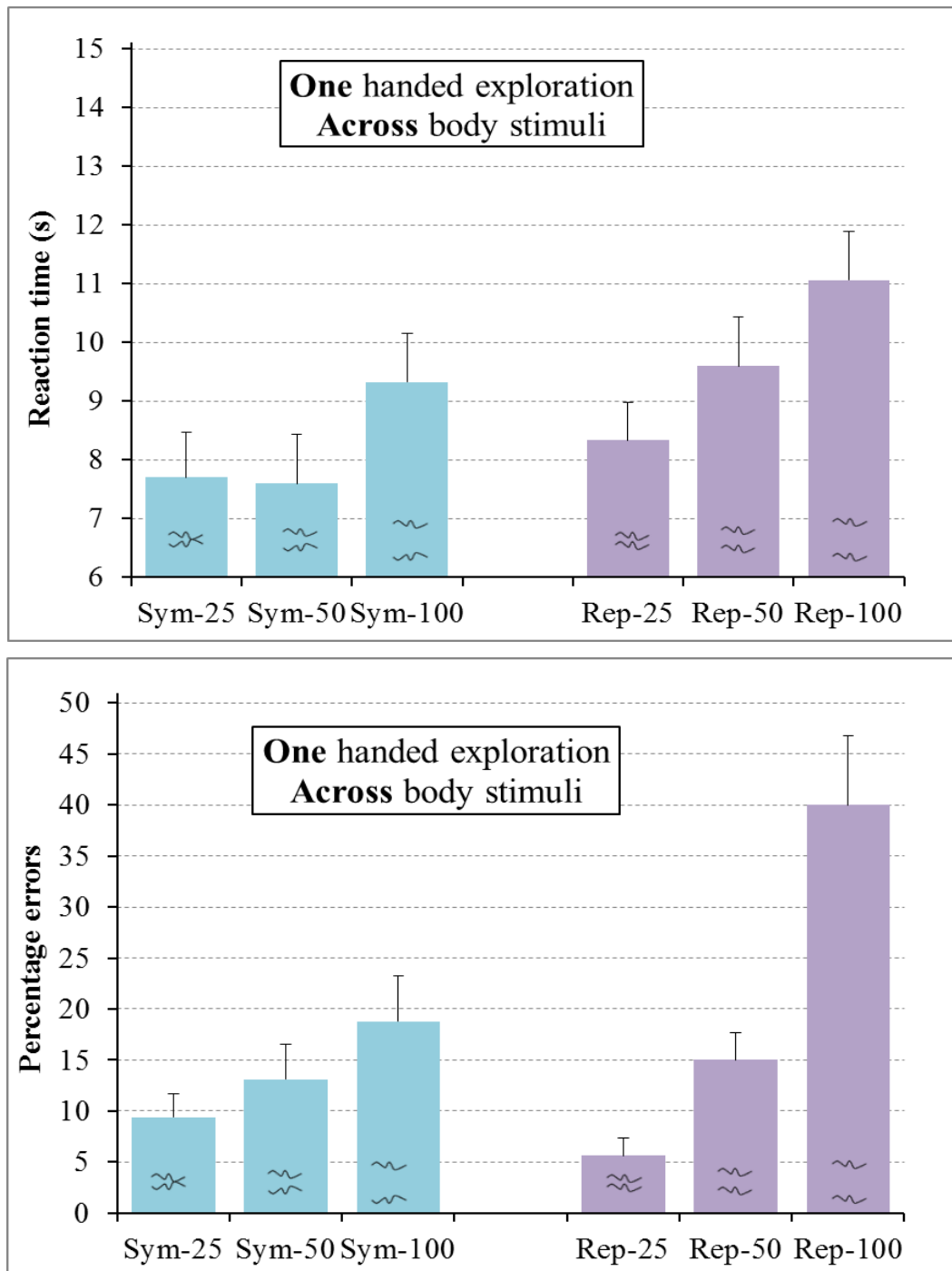


Figure 9. Results for regular trials for the one-handed exploration group in Experiment 3 for the haptic detection of symmetry (Sym) and repetition (Rep) for line separations of 25mm, 50mm and 100mm for RT (top) and errors (bottom). Error bars represent one standard error of the mean.

Two-handed exploration group

Participants used both of their index fingers to explore stimuli that were oriented to be perpendicular to their body midline. There were again two within-participants factors: regularity-type (symmetry or repetition) and line separation (small, medium or large).

Regularity-type was significant for both RT [$F(1,15) = 12.43$, $p = .003$, partial $\eta^2 = .45$] and errors [$F(1,15) = 37.27$, $p < .001$, partial $\eta^2 = .71$]. Symmetry detection (13.2s, 28% errors) was both slower and less accurate than repetition detection (10.7s, 9%). Note that this clear-cut advantage for detecting repetition contrasts to both the symmetry advantage found here for one-handed haptic exploration of across-body stimuli, and the symmetry advantage found in Experiment 2, for two-handed haptic regularity detection of body midline-aligned stimuli, as well as the symmetry advantage found in Experiment 1, for visual regularity detection of body midline-aligned stimuli. ANOVAs comparing the two groups tested in Experiment 3 and comparing the results of Experiment 2 to the two-handed exploration group in Experiment 3 are given in the Appendix.

Line separation was significant for RT [$F(2,30) = 5.38$, $p = .01$, partial $\eta^2 = .26$] but not for errors [$F(2,30) = 0.43$, $p = .6$, partial $\eta^2 = .03$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that regularity detection was slower for large separations (12.6s, 20% errors) than for medium (11.4s, 18%) and small (11.7s, 18%) separations, with no significant difference between medium and small separations.

The interaction of regularity-type \times line separation was not significant for RT [$F(2,30) = 0.17$, $p = .8$, partial $\eta^2 = .01$] or for errors [$F(2,30) = 1.18$, $p = .3$, partial $\eta^2 = .07$], see Figure 10, with a similar slowing at larger separations for symmetry and repetition detection.

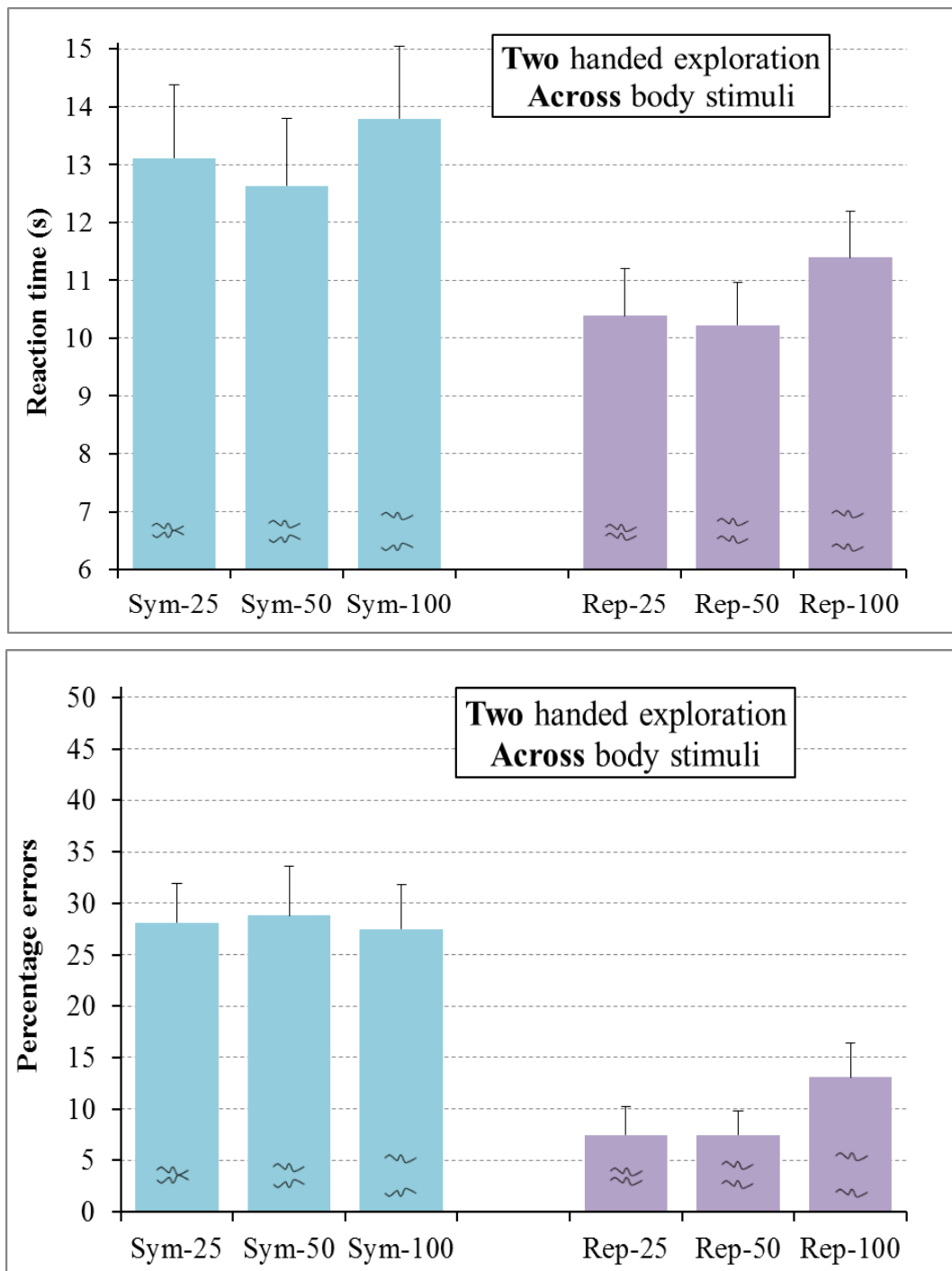


Figure 10. Results for regular trials for the two-handed exploration group in Experiment 3 for the haptic detection of symmetry (Sym) and repetition (Rep) for line separations of 25mm, 50mm and 100mm for RT (top) and errors (bottom). Error bars represent one standard error of the mean.

4.5.3 Discussion

The main findings from Experiment 3 involved interactions between regularity-type and three other factors: line separation, exploration type and stimulus orientation. We discuss each of these in turn. First, these results confirmed the difference between haptic and visual regularity detection which we observed when comparing the results of Experiments 1 and 2. For the two-handed exploration group, effects of line separation were similar for symmetry detection and for repetition detection, replicating the results for two-handed haptic exploration in Experiment 2, see Figure 10. For the one-handed exploration group, line separation influenced the accuracy of repetition detection more than that of symmetry detection, see Figure 9. This interaction was the reverse of the interaction which we observed for visual regularity detection, in Experiment 1, where increased line separation disrupted the detection of symmetry more than repetition. For vision, in Experiment 1, the results supported the hypothesis that small line separations and symmetry provide consistent evidence for the presence of a single object whilst large line separations and repetition provide consistent evidence for the presence of multiple objects. However, this account was not supported by the results for haptics, in Experiments 2 or 3.

Second, regularity detection was strongly influenced by whether one or two hands were used to explore across stimuli, where the axis of regularity ran perpendicular to the body midline. Symmetry was easier to detect than repetition for one-handed exploration whereas repetition was easier to detect than symmetry for two-handed exploration. These results were consistent with our predictions based on the hypothesis that both symmetry and one-handed exploration are cues for the presence of one object, whereas both repetition and two-handed exploration are cues for the presence of multiple objects.

Third, considering only two-handed exploration, in Experiment 2 symmetry was easier to detect than repetition when the axis of regularity of the stimuli was aligned with the body midline. Thus, here we found the usual symmetry advantage. In contrast, for the two-handed group in Experiment 3, repetition was easier to detect than symmetry when the axis of regularity ran across the body midline. This result suggests that, in Experiment 2 only, an

egocentric, body-centred (rather than an allocentric, world-centred) spatial frame of reference could be used to represent stimuli aligned with the body midline. Here symmetry detection was privileged relative to repetition detection because the axis of symmetry of the stimuli was coincident with a reference frame based on the axis of bilateral symmetry of the participant's own body. Thus, the orientation of stimuli relative to the body midline appears to play an important role in haptic symmetry detection.

We found an advantage for haptically detecting symmetry relative to repetition for both two-handed exploration of midline-aligned stimuli in Experiment 2, and for one-handed exploration of across-body stimuli in Experiment 3. Thus, an advantage for haptic detection of repetition occurred only when *both* the manner of exploration was consistent with a two-objects interpretation of the stimulus (i.e., two-handed exploration, favouring repetition detection) *and* when participants could not easily take advantage of body-centred spatial frames of reference (for across stimuli, where the axis of symmetry of stimuli was perpendicular to the axis of bilateral symmetry of the participant's own body). Thus, in general, symmetry appears to be easier to detect than repetition for haptics, consistent with what has long been established for vision (Julesz, 1971).

4.6 General Discussion

The present studies investigated two issues. First, we used truly repeated rather than anti-repetition stimuli to seek evidence for the claim that there is a one-object advantage for detecting symmetry and a two-objects advantage for detecting repetition (Koning & Wagemans, 2009; van der Helm & Treder, 2009). Second, we investigated whether effects found for regularity detection reflect internal, modality-specific processing or if they reveal differences arising directly from the presence of regularities out in the external, physical world. The overall motivation for examining these issues was to gain insights into what it means to be an object in vision and in touch. We manipulated three different potential cues to objectness: the type of regularity being detected, the separation between task-critical lines, and whether one hand versus two hands felt stimuli in haptic tasks. We hypothesised that symmetry, small line separations and one-handed

exploration would all provide evidence that a single object was present, whereas repetition, large line separations and two-handed exploration would all provide evidence that two objects were present. Our results revealed that regularity detection is strongly influenced by all three possible cues to objectness, and that these effects are modulated by the modality of stimulus presentation, and, for haptics, by the ease of use of egocentric, body-centred spatial reference frames. We found the predicted interaction of objectness by regularity-type in some, but not all, cases and this depended on whether stimuli were presented visually or haptically, as detailed below. We argue that these effects on regularity detection may mainly inform us about modality-specific encoding and processing strategies used by vision and touch and, thus, that they may not reflect intrinsic properties of objects in the physical world. Three of our results support this claim.

First, we compared line separation effects for haptic and visual regularity detection. In the context of visual perception, it has often been claimed that symmetry is used as a cue for the presence of a single, bilaterally symmetric object, whilst repetition is used as a cue for the presence of multiple, similarly shaped objects (Koning & Wagemans, 2009; van der Helm & Treder, 2009). These claims are plausible but, as reviewed in the Introduction, there is surprisingly little evidence for them. For line separation we investigated a novel prediction that during regularity detection our perceptual processes may take advantage of the fact that pairs of nearby lines are more likely to belong to a single object whereas pairs of more distant lines are more likely to belong to two different objects.

For vision, in Experiment 1, we found the predicted interaction between regularity-type (symmetry versus repetition) and the distance between lines. For vision, in Experiment 1, the cost of increased line separation was greater for symmetry than for repetition. This was as predicted since nearby, symmetrical lines provide consistent cues that a single object is present, whereas these cues are in conflict for well-separated, symmetrical lines. The opposite predictions were made for repetition, with well-separated, repeated lines providing consistent cues that multiple, similar objects are present, whereas these cues are in conflict for nearby, repeated lines. The results of Experiment 1 are consistent with our previous findings using symmetrical and

anti-repetition planar shapes (see Figure 2) where visual symmetry was easier to detect for one-object (as opposed to two-objects) stimuli and the reverse was true for repetition (Lawson & Cecchetto, 2015).

In contrast, for haptics, in Experiments 2 and 3, there was an overall advantage for detecting regularities across pairs of nearby (as opposed to well-separated) lines, but no reliable interaction between regularity-type and line separation. Instead, the cost of increased line separation was similar for symmetry and for repetition detection, except for the one-handed group in Experiment 3. In this latter case, the opposite interaction was found to that observed for vision, namely a greater advantage for nearby lines for detecting repetition than for symmetry. Again, these results are similar to our previous findings using planar shapes (Lawson & Cecchetto, 2015), where regularities were easier to detect within a single object (as opposed to across two objects) for both symmetry and repetition in haptics.

Thus, in both the present studies and in Lawson and Cecchetto (2015), we reliably found the predicted interaction between objectness and regularity-type for vision, but not for haptics. Thus, for vision, but not for haptics, these results are consistent with small line separations and symmetry providing consistent cues that a single object is present whilst large line separations and repetition provide consistent cues that two objects are present. We do not, as yet, have a good account of why vision and touch behave differently in this case. To address this issue, we have conducted further studies in which we have manipulated the time course of presentation of stimuli to vision and whether stimuli are presented all at once, or are viewed through a moving aperture (Cecchetto & Lawson, 2015).

Second, we tried to manipulate perceived objectness by changing how participants haptically explored the stimuli. We reasoned that pairs of lines explored with one hand are more likely to be interpreted as belonging to a single object, whereas pairs of lines explored with two separate hands may be more likely to be interpreted as belonging to two different objects.

To test this hypothesis, in Experiment 3 we compared haptic regularity detection of across stimuli using the index fingers of both hands, versus using the thumb and index finger of the right hand. Averaging over the effects of line separation, symmetry was easier to detect than repetition for one-handed exploration whereas the reverse was true for two-handed exploration. This

result is consistent with one-handed exploration and symmetry providing consistent cues that a single object is present whilst two-handed exploration and repetition provide consistent cues that two objects are present, making regularity detection easier overall in both cases. In contrast, regularity detection was harder overall when cues provided conflicting information about the number of objects present (for one-handed exploration of repetition, and for two-handed exploration of symmetry).

Regularity detection is probably also influenced by other aspects of haptic exploration which were not manipulated experimentally in the present studies. From pilot testing, and informal observation, it appears that regularity detection depends critically on aligning in time the inputs from exploring two, matched parts of a regular stimulus. In addition, the position of a finger on a contour or line (on the left or right side or on top) may influence how the shape of that edge is perceived. Future research should test how such changes in exploration strategies may influence the detection of regularities and the perception of objectness.

Third, we compared two-handed haptic regularity detection for stimuli aligned to the body midline of the participant (Experiment 2) and for the stimuli rotated so that the axis of regularity ran perpendicular to the body midline (Experiment 3). Symmetry was easier to detect than repetition for stimuli aligned with the body midline. Here, the body's own axis of bilateral symmetry provided a salient spatial frame of reference which was aligned with the axis of regularity of symmetrical stimuli. In contrast, repetition was easier to detect than symmetry when there was no privileged reference frame for symmetry detection because- the axis of regularity ran across the body midline.

Across all three of these comparisons, the same symmetrical and repeated stimuli were presented at the same line separations. Only the manner of processing differed across conditions (modality: vision versus haptics; manner of haptic exploration: one-handed versus two-handed; and orientation relative to the body: aligned versus across). Although the physical stimuli presented were not altered by these three manipulations, each had a clear effect on regularity detection, indicating the powerful influence of differences in perceptual encoding and processing.

Finally, we should highlight the fact that although in our studies we propose that we have manipulated several potential cues to objectness, even in vision, it has proven difficult to provide a formal definition of objectness (Feldman, 2003), whilst in haptics this topic does not appear to have been addressed at all. We do not claim that we have objectively varied objectness nor do we consider that objectness is a clear-cut, all-or-nothing attribute of stimuli. Previous studies which investigated the interaction between regularity detection and objectness using anti-repetition (Baylis & Driver, 1995; Bertamini et al., 1997; Bertamini, 2010; Koning & Wagemans, 2009; Lawson & Cecchetto, 2015) used a mixture of cues including closure, regularities, colour, luminance, 3D projections and stratification in depth to distinguish one-object from two-objects stimuli. Consistent with this approach, we suggest that multiple cues to objectness are extracted from perceptual inputs. Our results show that, in addition to those cues listed above, line separation and manner of exploration may play a significant role in specifying objectness. An important issue for future research will be to try to understand the relative importance of these cues in determining objectness, how they are combined and how any conflicts between them are resolved. In particular, the manipulations used in the present studies provide a promising means of investigating how objectness is specified for our sense of touch.

In conclusion, we found several interactions consistent with the predictions of an account that proposes that regularity-type, line separation and manner of exploration can all influence regularity detection because they are all informative about the nature of objectness. In contrast to the results for vision, the results for the interaction of regularity-type by line separation for haptics did not support this account. It is not clear why we did not obtain the latter interaction, but this result seems reliable given that we obtained a similar result when objectness was manipulated more directly, using planar shapes and anti-repetition (Lawson & Cecchetto, 2015, see Figure 2), rather than line separation and true repetition as used here. Together, these results inform us about, first, what cues may be used to determine objectness (regularity-type and line separation for vision; regularity-type and manner of exploration for haptics) and, second, what we can learn from effects on regularity detection. First, these results support the proposal that symmetry, small line separations (for vision but not haptics) and one-handed exploration (for haptics) are all

used as cues that a single object is present, whilst repetition, larger line separations (for vision but not haptics) and two-handed exploration (for haptics) are all used as cues that multiple objects are present. Regularity detection was influenced by all of these potential cues to objectness as well as by the spatial reference frame that could be used to represent the stimuli. Second, these results suggest that effects on regularity detection do not primarily reflect intrinsic, structural properties of physical objects in the world. Several of our manipulations had clear effects on regularity detection despite causing little or no change to physical properties of the stimuli, namely the modality of presentation, the manner of exploration and the availability of egocentric reference frames. Our findings instead suggest that regularity detection effects may be most informative about modality-specific differences in how stimuli are encoded and processed across vision and touch. This conclusion is consistent with the claims of Feldman (2003) that understanding the nature of objectness will involve specifying how our subjective, internal, perceptual representations are organised, rather than informing us about how the objective, external world is structured.

Footnotes

1 Due to a programming error in Experiment 1, the irregular trials for one of the 40 unique lines incorrectly showed regular stimuli, so the data for these six trials per participant were removed from all analyses.

2 Raw data is available to download from Experiment 1 at www.liv.ac.uk/~rlawson/GapPaperExpt1Data.txt, from Experiment 2 at www.liv.ac.uk/~rlawson/GapPaperExpt2Data.txt, and from Experiment 3 at www.liv.ac.uk/~rlawson/GapPaperExpt3Data.txt.

3 We speculate that this interaction might reflect the ease of controlling repeated versus symmetrical index finger and thumb movements as the right hand moves across the body during this task. We invite the reader to try this by moving their right hand across the surface of a table to follow imaginary lines.

4.7 APPENDIX - Further analyses

Additional ANOVAs were conducted on measures of sensitivity (d') and bias (c') for Experiments 1, 2 and 3 are described below, as well as ANOVAs comparing the two groups tested in Experiment 3, and comparing the results of Experiment 2 to the two-handed exploration group from Experiment 3:

Experiment 1 - sensitivity and bias analyses

For *sensitivity* (d'), regularity-type was not significant [$F(1,23) = 0.30$, $p = .59$, partial $\eta^2 = .01$]. Sensitivity was similar for symmetry detection (3.19) and repetition detection (3.14). Line separation was significant [$F(2,46) = 25.74$, $p < .001$, partial $\eta^2 = .53$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that sensitivity to regularity detection was greater with small separations (3.43) than with medium separations (3.11) and, in turn, that sensitivity was greater with medium separations compared to large separations (2.95). Finally, the interaction of regularity-type \times line separation was significant [$F(2,46) = 8.49$, $p = .001$, partial $\eta^2 = .27$]. To understand this interaction we calculated the difference between the sensitivity of regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This revealed that increased line separation (100mm - 25mm) caused a significantly greater reduction in sensitivity for detecting symmetry (0.76) than for detecting repetition (0.20) [$F(1,23) = 12.10$, $p = .002$, partial $\eta^2 = .35$].

For *bias* (c'), regularity-type was not significant [$F(1,23) = 0.10$, $p = .76$, partial $\eta^2 = .00$]. Bias was similar for symmetry detection (-0.09) and repetition detection (-0.08). Line separation was significant [$F(2,46) = 13.71$, $p < .001$, partial $\eta^2 = .37$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that bias was greater with small separations (-0.22) than either medium (-0.07) or large (.02) separations, with no difference between these two. Finally, the interaction of regularity-type \times line separation was significant [$F(2,46) = 6.74$, $p = .003$, partial $\eta^2 = .23$]. To understand this interaction we calculated the difference between the sensitivity of regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This revealed that increased line separation (100mm -

25mm) reduced bias more for detecting symmetry (0.38) than for detecting repetition (0.08), [F(1,23) = 10.78, $p = .003$, partial $\eta^2 = .32$]. A negative bias indicates a bias to say a regularity was present so this interaction reflected a greater bias to say that symmetry was present than that repetition was present at small line separations.

Experiment 2 - sensitivity and bias analyses

There were no significant effects for the *bias* analysis. For *sensitivity* (d'), regularity-type was significant [F(1,23) = 10.85, $p = .003$, partial $\eta^2 = .42$]. Sensitivity was greater for symmetry detection (1.92) than repetition detection (1.56). Line separation was significant [F(2,46) = 4.70, $p = .014$, partial $\eta^2 = .17$]. The overall pattern was for sensitivity to regularity detection to be greatest at small separations (1.95), inbetween for medium separations (1.66) and smallest for large separations (1.63). However, in post-hoc Newman-Keuls analyses only the difference in sensitivity between small and large separations was significant ($p < .05$). Finally, the interaction of regularity-type \times line separation was significant [F(2,46) = 3.94, $p = .026$, partial $\eta^2 = .15$]. This contrasts to the RT and error analyses on regular trials only reported in the main results section of Experiment 2. To understand this interaction we calculated the difference between the sensitivity of regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This revealed a significantly greater reduction in sensitivity at increased line separations (100mm - 25mm) for detecting symmetry (0.52) rather than repetition (0.17), [F(1,23) = 6.55, $p = .018$, partial $\eta^2 = .22$], as we now mention in the Discussion of Experiment 2.

Experiment 3 - One-handed exploration group - sensitivity and bias analyses

Participants used the thumb and index finger of their right hand only to explore stimuli that were oriented to be perpendicular to their body midline. There were two within-participants factors: regularity-type (symmetry or repetition) and line separation (small, medium or large).

For *sensitivity* (d'), regularity-type was significant [F(1,15) = 19.23, $p = .001$, partial $\eta^2 = .56$], with greater sensitivity for symmetry detection (1.93) than repetition detection (1.33). Line separation was also significant [F(2,30) =

28.044, $p < .001$, partial $\eta^2 = .65$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that sensitivity to regularity detection was greater at small separations (2.23) than at medium (1.54) separations which, in turn, was greater than at large (1.13) separations ($p < .05$). The interaction of regularity-type x line separation was not significant [$F(2,30) = 2.27$, $p = .1$, partial $\eta^2 = .13$].

For *bias* (c'), regularity-type was not significant [$F(1,15) = 1.33$, $p = .2$, partial $\eta^2 = .08$]. Line separation was significant [$F(2,30) = 4.38$, $p = .02$, partial $\eta^2 = .23$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that bias was greater at large (-0.06) than at medium (-0.35) separations with no significant differences involving small (-0.24) separations ($p < .05$). The interaction of regularity-type x line separation was significant [$F(2,30) = 8.75$, $p = .001$, partial $\eta^2 = .37$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that, for symmetry, there were no significant differences between bias at large (-0.19), medium (-0.22) and small (-0.10) separations, whereas for repetition, bias was greater at large (0.06) than at medium (-0.48) and small (-0.38) separations. To understand this interaction we calculated the difference between the sensitivity of regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This revealed that increased line separation (100mm - 25mm) altered bias for detecting symmetry (from -0.10 at 25mm to -0.19 at 100mm, a difference of -0.09) in the opposite direction to bias for detecting repetition (from -0.38 at 25mm to 0.06 at 100mm, a difference of 0.44), [$F(1,15) = 21.28$, $p < .001$, partial $\eta^2 = .59$]. A negative bias indicates a bias to say a regularity was present.

Experiment 3 - Two-handed exploration group - sensitivity and bias analyses

Participants used both of their index fingers to explore stimuli that were oriented to be perpendicular to their body midline. There were two within-participants factors: regularity-type (symmetry or repetition) and line separation (small, medium or large).

For *sensitivity* (d'), regularity-type was significant [$F(1,15) = 30.53$, $p < .001$, partial $\eta^2 = .67$]. Unlike the one-handed exploration group, sensitivity for the two-handed exploration group was less for symmetry detection (1.02) than for repetition detection (1.65). Line separation was not significant [$F(2,30) =$

0.45, $p = .6$, partial $\eta^2 = .03$]. Sensitivity was similar at small (1.30), medium (1.41) and large (1.29) separations. The interaction of regularity-type \times line separation was significant [$F(2,30) = 6.06$, $p = .006$, partial $\eta^2 = .29$]. To understand this interaction, we calculated the difference between the sensitivity of regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This revealed that the effect of increased line separation (100mm - 25mm) was significantly different on symmetry detection and repetition detection, [$F(1,15) = 8.43$, $p = .01$, partial $\eta^2 = .36$]. Increased line separation increased the sensitivity of detecting symmetry (by 0.31), but it reduced the sensitivity of detecting repetition (by 0.32). Thus, in the reverse of the results for visual regularity detection, increased line separation made symmetry detection easier but repetition detection harder.

For *bias* (c'), regularity-type was not significant [$F(1,15) = 17.25$, $p = .001$, partial $\eta^2 = .54$], with less bias for symmetry (-0.14) than for repetition (-0.47). Line separation was not significant [$F(2,30) = 0.71$, $p = .5$, partial $\eta^2 = .05$]. The interaction of regularity-type \times line separation was significant [$F(2,30) = 5.90$, $p = .007$, partial $\eta^2 = .28$]. To understand this interaction, we calculated the difference between the sensitivity of regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and conducted an ANOVA on these differences. This showed no significant difference of an increased line separation (100mm - 25mm) on the bias for detecting symmetry (0.11) and for detecting repetition (0.06), [$F(1,15) = 0.11$, $p = .7$, partial $\eta^2 = .01$].

Experiment 3 - Comparing the one-handed and two-handed exploration groups - RT and error analyses for regular trials and sensitivity analyses

There were two within-participants factors: regularity-type (symmetry or repetition) and line separation (small, medium or large) and one between-participants factor of exploration (one-handed or two-handed). Exploration was significant for RT [$F(1,30) = 6.85$, $p = .01$, partial $\eta^2 = .19$] but not for errors [$F(1,30) = 0.31$, $p = .5$, partial $\eta^2 = .01$]. Overall, one-handed exploration (8.9s, 17% errors) was faster than two-handed exploration (11.9s, 19%). In addition, two of the two-way interactions were significant for both RT and errors: for exploration \times regularity-type, for RT [$F(1,30) = 18.68$, $p < .001$, partial $\eta^2 = .38$],

for errors [$F(1,30) = 38.48$, $p < .001$, partial $\eta^2 = .56$]; for exploration x line separation, for RT [$F(2,60) = 4.22$, $p = .02$, partial $\eta^2 = .12$], for errors [$F(2,60) = 7.19$, $p = .002$, partial $\eta^2 = .19$]. The third interaction was significant for errors only: regularity-type x line separation, for RT [$F(2,60) = 1.38$, $p = .2$, partial $\eta^2 = .04$], for errors [$F(2,60) = 8.69$, $p < .001$, partial $\eta^2 = .22$]. The three-way interaction was not significant for RT and it was marginally significant for errors. The significant interactions arose mainly from the differences in performance of the two exploration groups, see Figures 9 and 10. ANOVAs conducted for each group separately are given in the results section of Experiment 3.

As in Experiment 1, we also calculated the difference between regularity detection for the largest (100mm) compared to the smallest (25mm) line separation and we then repeated the above ANOVA using these (100mm - 25mm) differences and without the line separation factor. Exploration was significant for both RT [$F(1,30) = 5.71$, $p = .02$, partial $\eta^2 = .16$] and errors [$F(1,30) = 10.42$, $p = .003$, partial $\eta^2 = .26$]. Increased line separation disrupted one-handed regularity detection (cost of 2.2s on RT and 22% on errors) much more than two-handed regularity detection (0.8s, 3%). This supports our hypothesis that small line separations and one-handed exploration provide consistent cues that a single object is present whilst large line separations and two-handed exploration both provide evidence that multiple objects are present. Regularity-type was not significant for RT [$F(1,30) = 1.47$, $p = .24$, partial $\eta^2 = .05$] but it was for errors [$F(1,30) = 16.53$, $p < .001$, partial $\eta^2 = .36$]. Increased line separation disrupted the accuracy of symmetry detection (cost of 1.2s on RT and 4% on errors) less than that of repetition detection (1.9s, 20%). This finding does not support the general claim that symmetry provides a cue for the presence of a single object whilst repetition provides evidence that multiple objects are present. Instead, this finding is consistent with the results of both Experiments 1 and 2 here, and Lawson and Cecchetto (2015), which suggest that there is a one-object advantage for symmetry detection and a two-objects advantage for repetition detection for vision, but not for haptics. Finally, the interaction of exploration x regularity-type was not significant for RT [$F(1,30) = 0.46$, $p = .50$, partial $\eta^2 = .02$] but it was for errors [$F(1,30) = 5.95$, $p = .02$, partial $\eta^2 = .17$]. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that, for the one-handed exploration group, increased line separation

disrupted accuracy less for symmetry (cost of 1.6s on RT and 9% on errors) than for repetition (2.7s, 34%) detection. For the two-handed exploration group, there was no significant difference in costs between symmetry (0.7s, 0%) and repetition (1.0s, 6%) detection. Note, though, that the trend (i.e., greater costs for repetition detection) was in the same direction as for the one-handed group, and it was opposite to our prediction.

For *sensitivity* (d'), regularity-type was not significant [$F(1,30) = 0.04$, $p = .8$, partial $\eta^2 = .00$]. Sensitivity was similar for symmetry detection (1.47) and repetition detection (1.49). Line separation was significant [$F(2,60) = 14.24$, $p < .001$, partial $\eta^2 = .32$]. Post-hoc Newman-Keuls analyses revealed that sensitivity to regularity detection was greater at small separations (1.76) than at medium (1.47) separations which, in turn, was greater than at large (1.21) separations ($p < .05$). In addition, the three two-way interactions were significant, though not the three-way interaction. For regularity-type \times line separation, [$F(2,60) = 7.25$, $p = .002$, partial $\eta^2 = .20$]; for regularity-type \times exploration, [$F(1,30) = 47.79$, $p < .001$, partial $\eta^2 = .61$]; and for line separation \times exploration, [$F(2,60) = 14.96$, $p < .001$, partial $\eta^2 = .33$].

Experiments 2 and 3 - Comparing two-handed exploration of midline-aligned stimuli (Experiment 2) versus across-body stimuli (Experiment 3) - RT and error analyses for regular trials

We conducted an ANOVA to compare the results of Experiment 2, in which 24 participants haptically explored stimuli where the axis of regularity was aligned with their body midline, and the two-handed group of Experiment 3, in which 16 participants haptically explored the same stimuli, but now oriented to be perpendicular to their body midline. All 40 participants used both of their index fingers to feel each pair of lines. There were two within-participants factors: regularity-type (symmetry or repetition) and line separation (small, medium or large), and one between-participants factor of alignment of the axis of regularity (aligned, in Experiment 2, or across, in the two-handed group of Experiment 3).

Alignment was significant for both RT [$F(1,38) = 12.15$, $p < .001$, partial $\eta^2 = .24$] and errors [$F(1,38) = 6.22$, $p = .02$, partial $\eta^2 = .14$]. Regularities were detected much faster and more accurately for aligned stimuli (7.9s, 12% errors)

than across stimuli (11.9s, 19%). As detailed below, the two-way interaction of alignment x regularity-type, and the interaction of alignment x line separation, were both significant, whilst neither the interaction of regularity-type x line separation, nor the three-way interaction, was significant for either RT or for errors (all F 's < 1.2). We presented the results for each of these two groups separately, in the results sections of Experiments 2 and 3, so here we will only discuss below the two significant interactions involving the factor of alignment. As before we also calculated the difference between regularity detection for the largest (100mm) compared to the smallest (25mm) line separation. We then repeated the above ANOVA using these (100mm - 25mm) differences. There were no significant effects in this ANOVA.

First, the interaction of alignment x regularity-type was significant for both RT [$F(1,38) = 19.68$, $p < .001$, partial $\eta^2 = .34$] and errors [$F(1,38) = 50.33$, $p < .001$, partial $\eta^2 = .57$]. Consistent with the separate group analyses already reported. Newman-Keuls analyses ($p < .05$) revealed that, for the aligned group, symmetry detection (7.2s, 8%) was faster and more accurate than repetition detection (8.7s, 16%), whereas the opposite was the case for the across group (13.2s, 28% for symmetry detection; 10.7s, 9% for repetition detection). Considering the two types of regularity separately, for symmetry detection the aligned stimuli were detected faster (by 6s) and more accurately (by 20%) than the across stimuli, as we had predicted. For repetition detection there was a speed-accuracy trade-off: aligned stimuli were detected faster (by 2s) but less accurately (by 7%) than across stimuli.

Second, the interaction of alignment x line separation was significant for RT [$F(2,76) = 3.49$, $p = .04$, partial $\eta^2 = .08$] but not for errors [$F(2,76) = 0.47$, $p = .6$, partial $\eta^2 = .01$]. Newman-Keuls analyses ($p < .05$) revealed that the across group were slower for large separations than for medium and small separations, whereas there was no significant difference between the three separations for the aligned group.

Chapter 5

5 The role of contour polarity, objectness and regularities in haptic and visual perception

* This study has been invited for resubmission as: Cecchetto, S & Lawson, R. (2015). The role of contour polarity, objectness and regularities in haptic and visual perception. (In preparation)

5.1 Abstract

Regularities such as symmetry (mirror-reflection) and repetition (translation) play an important role in both visual and haptic (active touch) shape perception. Altering figure-ground factors to change perceived objectness influences regularity detection. For vision, symmetry is usually easier to detect within one object whereas repetition is easier to detect across two objects, but for haptics we have found no effect of objectness, or a one-object advantage for both symmetry and repetition (Cecchetto & Lawson, 2016; Lawson, Ajvani & Cecchetto, 2016). However, our previous studies only used repetition stimuli with mismatched concavities and convexities. Such stimuli, with opposite contour polarities, are better described as anti-repetition stimuli (van der Helm & Treder, 2009) and may be processed differently to true-repetition stimuli. We investigated this possibility using new, true-repetition and anti-symmetry stimuli, as well as anti-repetition and true-symmetry stimuli. For haptics, symmetry and repetition detection was similar. Performance deteriorated strikingly with mismatched contour polarity (with objectness constant), whilst there was a modest disadvantage for 2objects (with contour polarity constant). For vision, symmetry detection was similar to haptics

(strong costs for mismatched contour polarity, weaker costs for 2objects) but repetition detection was very different (weak costs for mismatched contour polarity, strong costs for 1object). Thus contour polarity was more influential than objectness for symmetry detection regardless of modality, and for haptic repetition detection. However, for visual repetition detection, objectness effects reversed direction and were stronger than contour polarity effects, suggesting that regularity detection reflects information extraction and not merely regularity distributions in the physical world.

5.2 Introduction

Regularities like symmetry (mirror-reflection) and repetition (translation) provide important visual cues that we use to structure and organize information into meaningful elements (Palmer, 1989; Wagemans, 1995). These regularities are pervasive in our environment, frequently occurring in biological organisms (flowers, animals) as well as natural objects (waves, crystals) and manmade artefacts (vehicles and tools). Symmetry and repetition are also ubiquitous in crafts and architecture, where the need for structural stability converges with the desire to provide aesthetic pleasure to the observer.

We will begin by defining our terms since the terminology used by researchers to describe regularities is not consistent. In everyday language, symmetry is usually understood to refer only to bilateral, mirror-reflective symmetry. However, in the scientific literature, symmetry is often taken to include regularities such as repetition of a structure by a translation (translational symmetry) and 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-reflective symmetry, that we will refer to as *symmetry*, and translational symmetry, that we will term *repetition*. In the present study, we asked people to detect regular from irregular (random) stimuli. Regularities occurred across pairs of *critical contours*. These contours consisted of the outer left and right sides of a single object (henceforth *1object-outer-sides* stimuli), the two facing sides of two

objects (henceforth *2objects-inner-sides* stimuli) or the two right sides of two objects (henceforth *2objects-right-sides* stimuli), see Figure 1.

Vision scientists have long striven to understand how and why regularities are detected so efficiently by humans (for reviews, see Leeuwenberg, 2010; Treder, 2010; Tyler, 1995; van der Helm, 2014; Wagemans, 1995, 1997) and other animals (see, for example, Swaddle, 1999). Symmetry is known to provide a major grouping principle for the representation of visual shape (Palmer, 1989; Royer, 1981; Van der Helm & Leeuwenberg, 1996), for figure-ground segregation (Baylis & Driver, 2001; Driver, Baylis & Rafal, 1992; Machilsen, Pauwels & Wagemans, 2009), amodal completion (Kanizsa, 1985; van Lier, van der Helm & Leeuwenberg, 1995) and object recognition (Pashler, 1990; Vetter & Poggio, 1994). Bodily symmetry is associated with increased genetic quality and it may influence judgments of physical attractiveness (e.g., Grammer, Fink, Møller & Thornhill, 2003). It has been argued that the powerful and wide-ranging influence of regularities on perceptual processing may arise because symmetry and repetition in the 2D visual input provide us with important, proximal cues to non-accidental, distal properties of our 3D physical environment (Baylis & Driver, 1995).

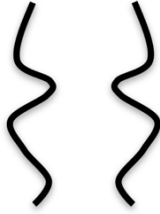
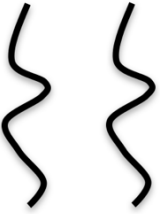
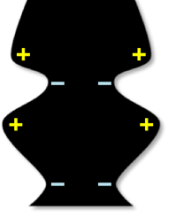

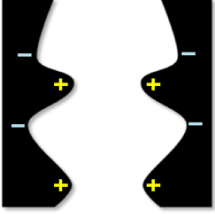


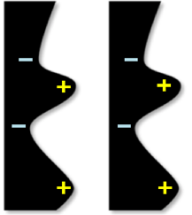
lines only	 <p>symmetry</p>	 <p>repetition</p>
1 object- outer-sides	 <p>==</p> <p>true - symmetry</p>	 <p>+/-</p> <p>anti - repetition</p>
2 objects- inner-sides	 <p>==</p> <p>true - symmetry</p>	 <p>+/-</p> <p>anti - repetition</p>
2 objects- right-sides	 <p>+/-</p> <p>anti - symmetry</p>	 <p>==</p> <p>true - repetition</p>

Figure 1. Examples of symmetrical (left) and repeated (right) regular stimuli. Irregular stimuli are not shown here, but they were identical to the regular stimuli except that the left and right critical contours were created from two different, unique lines. Top row: pairs of critical lines without surfaces, similar to the stimuli used by Lawson, Ajoani and Cecchetto (2016). Second and third rows: the same pairs of critical lines used to create the outline contours of 1object-outer-sides and 2objects-inner-sides stimuli, similar to the stimuli used by Cecchetto & Lawson (2016). Bottom row: the same pairs of critical lines incorporated into the new, 2objects-right-sides stimuli used in the present study. For the closed-contour shapes, contour polarity is indicated by plus signs (+) for convexities and minus signs (-) for concavities (concavities and convexities cannot be defined unambiguously for the line only stimuli since this would require labelling one side of the line as “inside”). Contour polarity either matched along equivalent points of the pairs of critical contours (indicated by ==) or mismatched (+/-). Bertamini, Friedenber and Kubovy (1997), Bertamini (2010),

Koning and Wagemans (2009) and Cecchetto and Lawson (2016) all only used 2objects stimuli like the 2objects-inner-sides stimuli that had true-symmetry but anti-repetition. Baylis and Driver (2001) only used 2objects stimuli like the 2objects-right-sides stimuli that had anti-symmetry and true-repetition. As far as we are aware, only Baylis and Driver (1995) have used the same six stimulus conditions as in the present study (i.e., all three lower rows of stimuli shown here), and they only tested visual (not haptic) regularity detection.

Understanding how and why the visual detection of symmetry and repetition differs.

It is well established that visual symmetry is easier to detect than other regularities such as repetition (Baylis & Driver, 1994, 1995; Mach, 1886/1959) and symmetry seems to have greater salience than repetition (Treder & van der Helm, 2007). Baylis and Driver (1994, 2001) suggested that this symmetry advantage could occur because symmetry within an object can be detected in parallel, whereas repetition must be processed serially. Their account was supported by their finding that symmetry detection, unlike repetition detection, was not affected by contour complexity (manipulated by varying the number of discontinuities; see also Lawson & Cecchetto, in preparation). They suggested that symmetry could rely on efficient parallel processing (but only when the pairs of critical contours belonged to a single symmetrical object, see Baylis & Driver, 2001), whereas repetition required an effortful and time-consuming, point-by-point comparison of each discontinuity along a pair of contours.

Baylis and Driver (1995) noted that equivalent points along pairs of critical contours on either side of an object have matching polarities of concavity and convexity for symmetrical stimuli, whereas contour polarity mismatches for repetition stimuli, as in the second row of Figure 1. They argued that the symmetry advantage for 1object stimuli arose because contour polarities matched, allowing the object to be readily segmented into parts. Their account was based on Hoffman and Richards' theory of part decomposition (Hoffman & Richards, 1984; see also Hoffman & Singh, 1997; Lim & Leek, 2012). Hoffman and Richards (1984) suggested that an object's shape can be represented in terms of the layout of its convex parts, with adjacent parts being separated by points of concavity, that they referred to as

negative minima of curvature. However, for 1object, repetition stimuli both contour polarities and part decomposition mismatch (for a recent review on contour polarity, see Bertamini & Wagemans, 2013). The detection of repetition might therefore necessitate an inefficient, serial processing of vertices.

Understanding the symmetry advantage in regularity detection also requires explaining the well-established finding of an interaction between regularity-type and objectness (Koning & Wagemans (2009; see also Baylis & Driver, 1995, 2001; Bertamini, FriedenberG & Kubovy, 1997; Cecchetto & Lawson, 2016; Lawson et al., 2016). The exact nature of this interaction varies across different studies (Koning & Wagemans, 2009). However, in general, symmetry detection is better when the critical contours belong to the outer sides of the same object (1object-outer-sides stimuli) rather than the facing sides of 2objects (2objects-inner-sides stimuli) whereas repetition detection is easier when the critical contours belong to 2objects-inner-sides stimuli rather than 1object-outer-sides stimuli. These results cannot be explained by the account of Baylis and Driver (1995) just outlined, because any effects of contour polarity on parts decomposition should be the same for 2objects-inner-sides stimuli and 1object-outer-sides stimuli (see rows 2 and 3 of Figure 1 respectively). Instead, some factor other than part decomposition must be driving the regularity-type by objectness interaction.

Koning and Wagemans (2009; see also Cecchetto & Lawson, 2016; Lawson et al., 2016; Treder & van der Helm, 2007; van der Helm & Treder, 2009) argued that the regularity-type by objectness interaction might arise because symmetry and repetition provide different cues about the world. Visual regularities may provide important information about how to segment a scene into objects, with symmetry used to signal the presence of a single object, and repetition used to indicate the presence of multiple, similarly shaped objects (Cecchetto & Lawson, 2016). This could then explain why symmetry is easier to detect when it occurs within a single object (for 1object-outer-sides stimuli) whilst repetition is easier to detect when it occurs across different objects (for 2objects-inner-sides stimuli).

An important limitation with most research conducted to date comparing symmetry and repetition detection arises from a confound

between regularity type and contour polarity. Specifically, symmetrical stimuli usually had matching contour polarity so could be described as truly-regular but the repetition stimuli had mismatching contour polarity (with respect to colour, luminance and/or curvature, namely concavities and convexities) and so might be best described as anti-regular (see the 1object-outer-sides and 2objects-inner-sides stimuli shown in rows 2 and 3 of Figure 1). This was the case for most studies that have investigated the interaction between regularity-type and objectness (e.g., Bertamini et al., 1997; Bertamini, 2010; Cecchetto & Lawson, 2016; Koning & Wagemans, 2009; Lawson et al., 2016). Van der Helm and colleagues have highlighted the importance of distinguishing between true-regularities and anti-regularities (Csathó, van der Vloed & van der Helm, 2003; van der Helm & Treder, 2009). Van der Helm and Treder (2009) found evidence that the visual system treats anti-regularities differently to true-regularities. They suggested that only Corballis and Roldan (1974) and Treder and van der Helm (2007) investigated the interaction of regularity-type by objectness for true-symmetry and true-repetition stimuli. Corballis and Roldan (1974) used pairs of dot patterns that were either shown adjacent to each other (so they could be perceived as a single object) or separated by a gap (so they would be perceived as two distinct objects). Their task was unusual in that participants had to discriminate regularity type (symmetry versus repetition) with no irregular stimuli being presented. Treder and van der Helm (2007) used symmetrical and repeated dot patterns presented stereoscopically. They relied on grouping principles to ensure that sets of dots were perceived as a single object (because they lay on the same depth plane) or two distinct objects (because the dots lay on two different depth planes). In both studies, the interaction (symmetry detection being easier for 1object compared to 2objects stimuli, and vice versa for repetition detection) was found only for dot stimuli, and in neither study was a clear, 2objects advantage found for repetition. In summary, there is little evidence that true-repetition (as opposed to anti-repetition) is easier to detect visually for 2objects stimuli relative to 1object stimuli.

Haptic regularity detection

One way to progress our understanding of how and why we are sensitive to symmetry and repetition is to find a new approach to test regularity detection. To achieve this, we have investigated a different modality since a limitation of the literature reviewed so far is that it has only investigated the visual detection of regularities. Many objects can also be efficiently recognized and detected by haptics, our sense of active touch. Vision and haptics extract information from similar environments and share many processing goals. Both modalities can efficiently achieve object constancy in order to identify many of the same objects using a similar set of spatial features, such as object shape, size and orientation (e.g., Craddock & Lawson, 2008, 2009; Jones & Lederman, 2006; Lawson, 2009). Object naming using haptics alone is fast and accurate (~2s and <10% errors) though it is slower and less accurate than visual object recognition (Lawson & Bracken, 2011). By comparing vision to haptics we can assess whether any effects on regularity detection generalise and hence whether they may reflect the pattern of occurrence of regularities in our external, physical world. Alternatively, the extent to which effects on regularity detection are modality-specific indicates the importance of stimulus exploration and information extraction and storage.

Compared to research on visual regularity detection, there has been relatively little research investigating the haptic perception of symmetry (for a recent review, see Cattaneo, Bona, Bauer, Silvanto, Herbert, Vecchi & Merabet, 2014). Nevertheless, it is well established that haptics can detect symmetry (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; Cecchetto & Lawson, 2016; Lawson et al., 2016; Lawson & Cecchetto, in preparation; Locher & Simmons, 1978; Millar, 1978). As far as we are aware, we are the only researchers to have investigated the perception of repetition by haptics (Cecchetto & Lawson, 2016; Lawson et al., 2016). We have confirmed that it, too, can readily be detected by haptics.

In order to try to contrast regularity detection in vision and in haptics, and to specify its role in object perception, we have investigated several

potential cues to objectness. Across a series of studies, we have manipulated modality-independent factors, such as regularity-type (symmetry versus repetition) and line separation, as well as modality-specific cues. We have found both similarities and differences between visual and haptic regularity detection. In general, we have observed an advantage for detecting symmetry relative to repetition for both modalities, but different effects of objectness on this basic effect (Cecchetto & Lawson, 2016; Lawson et al., 2016; Lawson & Cecchetto, in preparation). Specifically, we have replicated the regularity-type by objectness interaction for vision (driven mainly by a 2objects-inner-sides advantage for repetition detection), but for haptics we found no effect of objectness for either symmetry or repetition detection for stimuli with the axis of symmetry aligned with the body midline. This modality-specific difference in the effects of objectness indicates that regularity detection does not solely reflect external properties of our physical environment. The 3D objects that generated the input stimuli for vision and for haptics were constant across all four regularity-type by objectness conditions. No modality-specific effects should have occurred if effects on regularity arise only from our perceptual systems making use of cues about objectness that can be inferred from the pattern of their occurrence in the external, physical world.

As discussed already, one concern raised by van der Helm and colleagues is that most of the stimuli used in previous studies confounded effects of regularity type and contour polarity, leading to a paucity of direct evidence that true-repetition is easier to detect for 2objects compared to 1object stimuli. Lawson et al., (2016) addressed this issue by comparing the haptic and visual detection of regularities for pairs of critical lines separated by small, medium or large gaps (see the top row of Figure 1). Using line-only stimuli, rather than contours belonging to planar surfaces, avoided the problems raised by Van der Helm and Treder (2009) with respect to true-repetition and anti-repetition, because concavities and convexities cannot be defined unambiguously for line-only stimuli. We predicted that nearby lines were more likely to be grouped together, and hence to be perceived as belonging to a single object, whilst well-separated lines would not be grouped together, and so would be more likely to be perceived as belonging to two different objects. These effects were predicted to interact with the influence of regularity type in defining objects, namely that symmetry may be used as a cue for the

presence of a single object whilst repetition is used as a cue for the presence of multiple, similarly-shaped objects. Thus, the detection of symmetry should be easier for nearby lines because both nearby lines and symmetry may be cues for the presence of one object with the opposite occurring for repetition. For vision, as predicted, increased line separation disrupted symmetry detection more than repetition detection. However, for haptics, symmetry and repetition detection were similarly disrupted by increased line separation. Thus, the interaction between regularity-type and objectness found for vision was not found for haptics, consistent with the results reported by Cecchetto and Lawson (2016) for closed-contour, planar shapes.

However, one concern with all three of the studies that have been proposed to have manipulated objectness without using anti-repetition stimuli (Corballis & Roldan, 1974; Lawson et al., 2016; Treder & van der Helm, 2007) is that they used stimuli that might not be considered as objects (either small sets of dots or pairs of lines). It is difficult to formally define what is an object (Feldman, 2013) despite the importance of objectness to both perception and cognition. Furthermore, researchers claiming to manipulate objectness often make little attempt to justify their choice of stimuli. Nevertheless, stimuli comprising dots or lines lack many of the features that are typical of everyday objects, such as having closed-contours and solid surfaces. Worse still, the dot stimuli used by Corballis and Roldan (1974) and Treder and van der Helm (2007) and the line-only stimuli used by Lawson et al., (2016) may be trapped in a Catch-22 situation. If they are *not* interpreted as objects then they do not seem suitable stimuli to use to investigate objectness. However, crucially, if they *are* perceived as objects then, arguably, that is because they are perceived to have a contour-bounded shape (for example, created by joining adjacent dots or by connecting the nearest ends of lines together). An extensive literature in visual perception has shown that people can behave as if contours are present in some circumstances, for example in illusions involving amodal completion such as Kanizsa's triangle (Kanizsa, 1976). If the stimuli used by Corballis and Roldan (1974), Treder and van der Helm (2007) and Lawson et al., (2016) were perceived as contour-bounded shapes then the vertices of these contours would have polarities defined by concavities and convexities. If so then these stimuli would fall foul of the confound between regularity-type and

contour polarity already outlined. We should note that we think that multiple cues combine to determine the extent to which a given (part of a) stimulus is perceived as an object so we do not assume that objectness is an all-or-nothing property of a stimulus. On this view, dot and line stimuli may possess some qualities of an object but they may not be perceived as objects as often, or as unambiguously, as closed-contour, planar shapes. Given the difficulties of deciding on the objectness of dot and line stimuli we felt that it was important to try to independently assess the role of matching versus mismatching contour polarity and of objectness on regularity detection using planar shapes with well-specified, unambiguous bounding contours and surfaces. This was the goal of the study reported here.

In summary, in the present study, we aimed to tease apart the roles of contour polarity and objectness by comparing regularity detection for a new set of stimuli, the 2objects-right-sides stimuli shown in the bottom row of Figure 1, in addition to the 1object-outer-sides and 2objects-inner-sides stimuli used in our previous studies. We thus tested 1object conditions with true-symmetry and with anti-repetition, and 2objects conditions with all four combinations, namely true-symmetry, anti-symmetry, true-repetition and anti-repetition. We compared symmetry and repetition detection by haptics (Experiment 1) and by vision (Experiment 2) using stimuli similar to those used by Baylis and Driver (1995) who investigated visual (but not haptic) regularity detection. In each experiment we focussed on two comparisons. First, we investigated the role of objectness by comparing 1object to 2objects conditions with contour polarity held constant (by only considering true-symmetry detection using matching contour polarity stimuli and anti-repetition detection using mismatching contour polarity stimuli). Second, we investigated the role of contour polarity by comparing stimuli with matched to mismatched contour polarities with objectness held constant (for 2objects stimuli only; we compared the detection of true-symmetry to anti-symmetry and, separately, we compared the detection of true-repetition to anti-repetition). Note that it was not possible to fully cross the factors of objectness (one versus two) and contour polarity (matching for truly-regularity stimuli versus mismatching for anti-regular stimuli) for our shapes, which was why we conducted two separate comparisons.

5.3 Experiment 1

Participants haptically explored unseen, planar shapes and, for each stimulus, decided if it included a pair of regular contours. Symmetry detection and repetition detection were tested in separate blocks. We expected to replicate the finding of Cecchetto and Lawson (2016) of an overall advantage for symmetry detection and also of no interaction between regularity-type and objectness. As far as we are aware, effects of contour polarity have not been investigated for haptics.

5.3.1 Method

5.3.1.1 *Participants*

There were 24 participants (16 females, mean age = 20 years, s.d. = 4.5 years, range = 18-40). They were either volunteers or undergraduate students from the University of Liverpool, who participated for course credit, and who reported no known conditions affecting their sense of touch. All participants completed the Edinburgh Handedness Inventory, that revealed two left-handers, one female and one male (mean score = 91.7, range = 100, -100). Both the experiments reported here received ethical approval from the local ethics committee.

5.3.1.2 *Materials*

A laser cutter was used to produce the stimuli from 5mm thick black acrylic sheets. Twelve stimuli (regular / irregular x symmetry / repetition x 1object-outer-sides / 2objects-inner-sides / 2objects-right-sides) were created from each of 20 unique lines to produce a set of 240 stimuli. The 240 stimuli were each glued onto a 10cm x 10cm brown cardboard base. The unique lines each had four vertices and were a subset of those used by Cecchetto and Lawson (2016). They were chosen by ordering our previous set of 40 unique lines by the overall accuracy of regularity detection for each line, then selecting alternate lines so the lines used spanned the range of difficulty. Further details

about the creation of the unique lines are given in Cecchetto and Lawson (2016) and in Lawson et al., (2016). Cecchetto and Lawson (2016) used unique lines with straight segments only. Here, the lines were smoothed to give rounded vertices to ensure that the participant's fingers could feel around them. Irregular stimuli were created by pairing each unique line with a different unique line. Each critical contour was defined by a unique line. All six regular stimuli created from a given unique line included the same two critical contours and the same was true for all six irregular stimuli created from that unique line. Only the location of the surface and the nature of the regularity (symmetry or repetition) changed across each subset of six stimuli. The surface lay between the two critical contours for 1object-outer-sides stimuli, it was on the outside of the two contours for 2objects-inner-sides stimuli, and it was on the left side of each contour for 2objects-right-sides stimuli, see Figure 1.

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, see Figure 2. Participants responded using one of two foot pedals. On the table in front of the curtain there were two labels, "same" on the left and "different" on the right, to remind participants which foot-pedal they should use to respond to regular and irregular stimuli respectively. Participants were told to centre their body midline with the midpoint of the two response labels and the two foot-pedals. Stimuli were placed with the nearest side 20cm from the edge of the table and approximately 45cm from the participant's body. Stimuli were slotted into a fixed foam-board frame with a 10.1cm x 10.1cm aperture (see Figure 2). The frame prevented the stimuli from moving during haptic exploration. Stimuli were always presented with the axis of regularity of the critical contours aligned with the participant's body midline. Two white, textured patches were placed above the top of each of the critical contours to mark the resting positions for each index finger, and to ensure that the critical contours were easy to locate. The centres of the patches were 5cm apart.

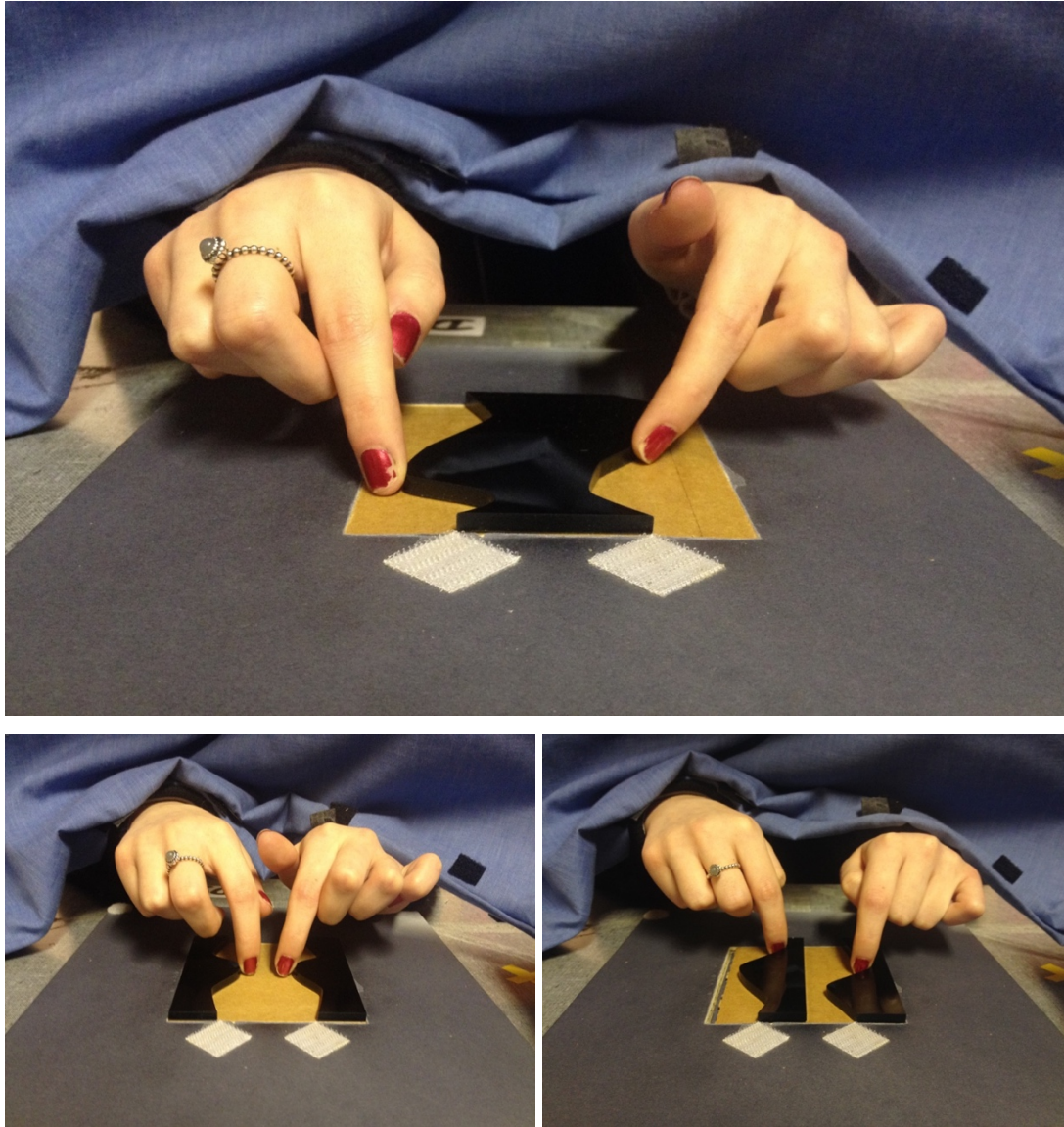


Figure 2. Examples of haptic exploration of an irregular, 1object-outer-sides stimulus (top), a symmetrical, 2objects-inner-sides stimulus (bottom left) and an irregular, 2objects-right-sides stimulus (bottom right) in Experiment 1, as seen from the experimenter's point of view. Two white diamond patches marked the rest positions and were located above the top of each of the critical contours of the stimulus.

5.3.1.3 Design

The 240 stimuli were divided into two equal subsets. Each participant was presented with one subset. Within this subset each of the 20 unique lines appeared as the left critical contour three times for symmetrical stimuli (once

per stimulus condition) and three times for repetition stimuli (once per stimulus condition). Participants completed two blocks of 60 trials, one testing symmetry detection and the other testing repetition detection. Within each block, half the stimuli were regular and half were irregular, with ten of each type from each stimulus condition (1object-outer-sides, 2objects-inner-sides and 2objects-right-sides). Trials were presented in a fixed, pseudo-random order. Half of the participants detected symmetry first and the remainder detected repetition first. Six participants from each of these two groups were assigned to each of the two stimulus subsets.

5.3.1.4 Procedure

Prior to starting the experiment participants, were told about the regularity-type (symmetry or repetition) that they had to detect in the first block. They were then visually shown six examples of the type of stimuli that they were about to feel (one regular and one irregular for each of the three stimulus conditions). These stimuli were similar to the experimental stimuli but they were not included in the experimental set. Participants then performed six practise trials feeling each of the practise stimuli in turn. They were told to respond as quickly and accurately as possible, to explore the two critical contours simultaneously, to use one index finger to feel each critical contour, and not to rotate, move, or pick up the stimuli.

At the start of each trial the experimenter placed a stimulus in the frame whilst the participant kept their hands on the resting position patches for each hand, see Figure 2. The experimenter then triggered an auditory 'go now' signal from the computer. This signal indicated that the participant could move their hands down from the resting positions to feel the stimulus. Reaction times were measured from the offset of the 'go now' signal until the participant responded by pressing the foot pedal. This triggered a high or a low pitch feedback sound that indicated whether their response was correct or wrong respectively. The first experimental block began immediately after the six practise trials. At the end of this block participants were told about the new type of regularity that they would have to detect and they were visually shown six new practise stimuli. They then did six practise trials

followed by the second block. Finally, participants were asked whether they had seen any of the stimuli. The experiment took about 50 minutes.

5.3.2 Results

No participants were replaced and none reported that they had seen any of the stimuli. 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. Correct RT faster than 1s or slower than 35s were discarded as errors (less than 1% of trials). In the ANOVAs there were two within-participants factors: regularity-type (symmetry or repetition) and condition (1object-outer-sides, 2objects-inner-sides or 2objects-right-sides). All pairwise differences noted below were significant ($p < .05$) in post-hoc Newman-Keuls analyses. Appendix 1 gives the full ANOVAs for RT, errors and sensitivity (d'). Here, we focus on the theoretically important effects so we only report the results for the interaction of regularity-type \times condition and the results for the two critical comparisons.

The interaction of regularity-type \times condition was significant for RT [$F(2,46) = 34.86, p < .001, \text{partial } \eta^2 = .60$], errors [$F(2,46) = 90.47, p < .001, \text{partial } \eta^2 = .79$] and sensitivity [$F(2,46) = 28.10, p < .001, \text{partial } \eta^2 = .55$], see Figure 3.

First, we considered whether variation in objectness influenced haptic regularity detection when contour polarity was held constant, by comparing performance for 1object-outer-sides stimuli to 2objects-inner-sides stimuli. For true-symmetry detection, there was no significant difference between 1object-outer-sides stimuli (7.1s, 3%, d' of 2.08) and 2objects-inner-sides stimuli (8.1s, 5%, 1.87). For anti-repetition detection, 1object-outer-sides stimuli (10.0s, 39%, 1.05) were detected faster, but no more accurately or more sensitively, than 2objects-inner-sides stimuli (11.9s, 46%, 0.95). Thus, here the overall trend was for a weak 1object advantage for both symmetry and repetition detection, with this difference only significant for RT for repetition.

Second, we investigated whether contour polarity influenced haptic regularity detection when objectness was held constant, by comparing performance for 2objects-inner-sides stimuli to 2objects-right-sides stimuli. True-symmetry, 2objects-inner-sides stimuli (8.1s, 5%, 1.87) were detected

faster, more accurately and more sensitively than anti-symmetry, 2objects-right-sides stimuli (11.7s, 67%, 0.19). Indeed, people were unable to detect symmetry in the anti-symmetry conditions (67% wrong "irregular" responses for regular trials versus 73% correct "irregular" responses for irregular trials). Anti-repetition, 2objects-inner-sides stimuli (11.9s, 46%, 0.95) were detected slower and less accurately than true-repetition, 2objects-right-sides stimuli (8.5s, 3%, 1.20), with the same trend for sensitivity but this latter difference was not significant in post-hoc Newman-Keuls analyses. Thus, for both symmetry and repetition, true-regularities were much easier to detect than anti-regularities.

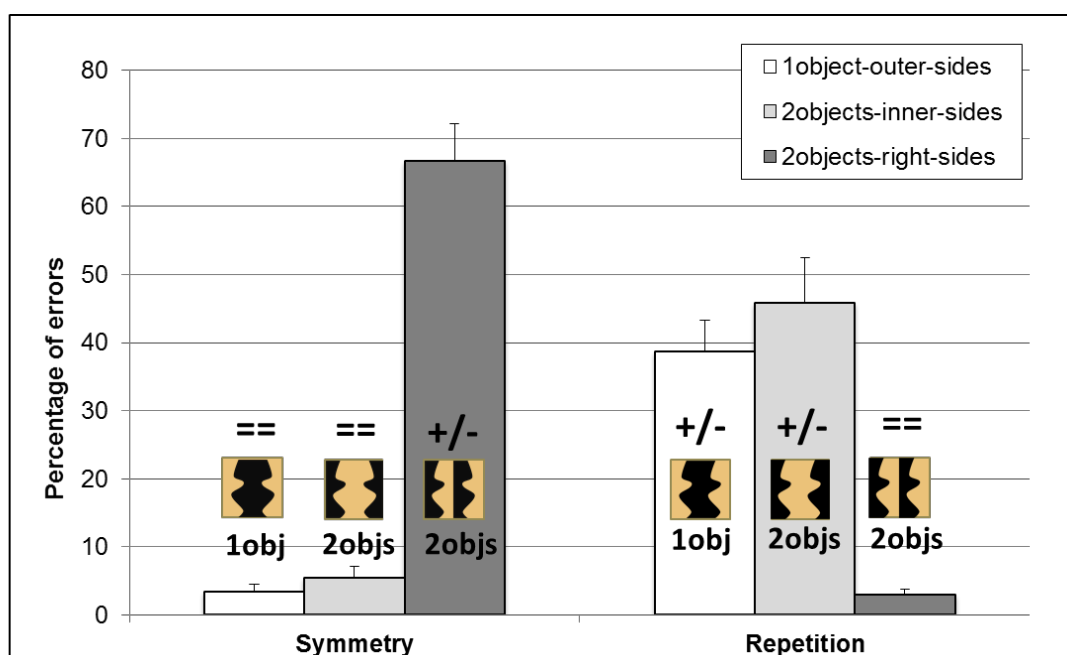
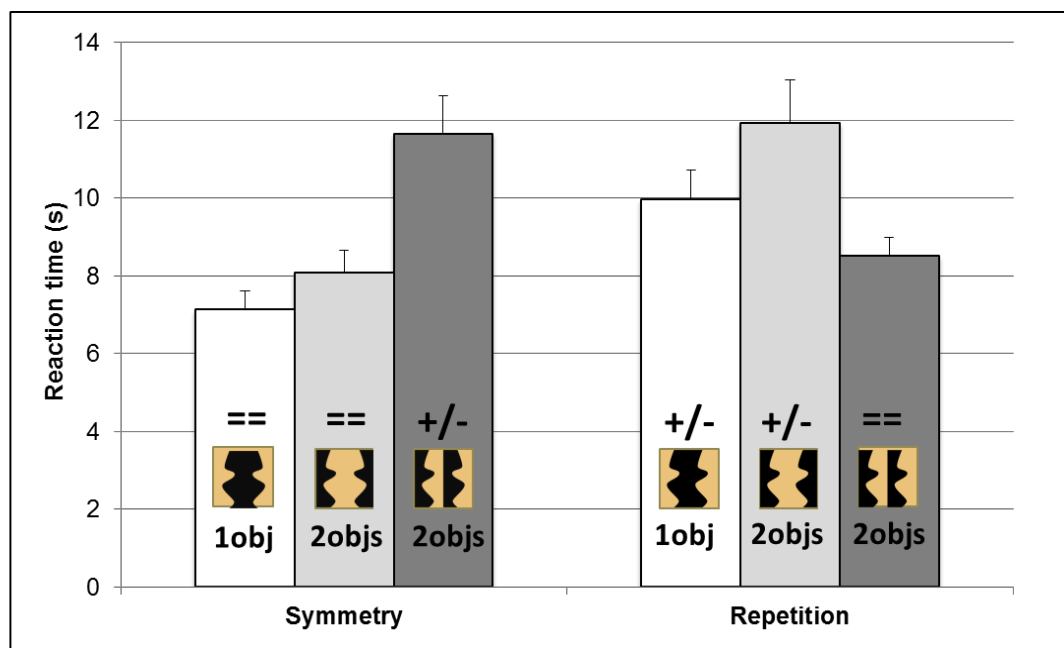


Figure 3. Results in Experiment 1, for regular trials, for the haptic detection of symmetry and repetition, for 1object-outer-sides (white bars), 2objects-inner-sides (light grey bars) and 2objects-right-sides stimuli (dark grey bars), for RT (top), and errors (bottom). Error bars represent one standard error of the mean. Example stimuli from each condition are shown on or above each bar, with a black object against a light brown background. Above each example stimulus, symbols indicate whether contour polarity across the pairs of critical contours matched (==) or mismatched (+/-). Below each example stimulus, the labels "1obj" and "2objs" indicate whether the critical contours both belonged to a single object or each belonged to a different object respectively.

5.3.3 Discussion

In Experiment 1, we compared the haptic detection of true-regularities and anti-regularities for closed-contour, planar shapes (see Figure 1). We investigated, first, the role of objectness (one versus two objects) and, second, contour polarity (matched versus mismatched concavities and convexities for truly-regular and anti-regular stimuli respectively) in the perception of symmetry and repetition.

First, we found little influence of varying objectness when contour polarity was held constant. Performance was similar whether pairs of critical contours belonged to a single object (for the 1object-outer-sides stimuli) or to two objects (for the 2objects-inner-sides stimuli). For these comparisons, contour polarity always matched for symmetry detection (all stimuli had true-symmetry) and always mismatched for repetition detection (all stimuli had anti-repetition, see Figure 1). Overall, there was a modest 1object advantage but this was only significant for the speed of repetition detection. Crucially, performance was similar for symmetry detection and repetition detection, so there was no objectness by regularity-type interaction.

Cecchetto and Lawson (2016) used similar stimuli to these 1object-outer-sides and 2objects-inner-sides stimuli, though in Experiment 1 here we only used half of the unique lines as in that study, and the present stimuli were made of plastic rather than foamboard, and had rounded rather than straight vertices. Despite these differences, the results here replicated our previous

haptic findings with, critically, no 2object advantage for repetition detection and no interaction between objectness and regularity-type.

Second, we investigated the role of contour polarity by comparing stimuli with matched to mismatched concavities and convexities when objectness was held constant (by testing only 2objects stimuli). We compared performance for true-symmetry to anti-symmetry stimuli, and for true-repetition to anti-repetition stimuli (see Figure 1). The 2objects-right-sides stimuli produced a strikingly different pattern of performance to the 2objects-inner-side stimuli, with opposite effects depending on the type of regularity being detected, see Figure 3. Consistent with the claim that anti-regularities are harder to detect than true-regularities (Van der Helm & Treder, 2009). Anti-symmetry was much harder to detect than true-symmetry (indeed people were unable to discriminate between the anti-symmetry conditions), whilst anti-repetition was much harder to detect than true-repetition. These results show that contour polarity plays a crucial role in haptic shape perception.

5.4 Experiment 2

Experiment 2 largely replicated Experiment 1 except that the stimuli were presented visually, as pictorial images on a vertical monitor, rather than haptically, as 3D, planar shapes. We presented the same conditions as in Experiment 1 (regular / irregular x symmetry / repetition x 1object-outer-sides / 2objects-inner-sides / 2objects-right-sides) to the same participants. In doing so we replicated the visual regularity detection conditions tested by Baylis and Driver (1995; see also Figure 1), though many of the details of the design, task and stimuli differed.

In Experiment 2 we investigated whether a different pattern of effects on regularity detection would be found for vision than we found for haptics in Experiment 1. In Experiment 1, unlike previous results for visual regularity detection, but replicating our earlier findings for haptic regularity detection (Cecchetto & Lawson, 2016; Lawson et al., 2016), there was no 2objects advantage for repetition detection and no interaction between objectness and regularity-type. In addition, we found a new result, a powerful advantage for true-regularities over anti-regularities.

First, we investigated the role of objectness when contour polarity was held constant. Unlike for haptics as tested in Experiment 1, we predicted that we would obtain a regularity-type by objectness interaction, consistent with previous results obtained from testing visual regularity detection for planar shapes (e.g., Baylis & Driver, 1995; Bertamini et al., 1997; Cecchetto & Lawson, 2016; Koning & Wagemans, 2009; Lawson, Ajvani & Cecchetto, 2016). We expected to find a 1object advantage for symmetry detection but a 2objects advantage for repetition detection. This would be consistent with symmetry being used as a cue to the presence of a single object and repetition being associated with the presence of multiple, similarly shaped objects in the external, physical world (Cecchetto & Lawson, 2016; Lawson et al., 2016).

Second, we investigated the role of contour polarity when objectness was held constant. We predicted that, as for haptics in Experiment 1, anti-regularities would be harder to detect than true-regularities (Van der Helm & Treder, 2009). The only previous studies that we are aware of that have tested 2objects-right-sides stimuli were reported by Baylis and Driver (1995, 2001). Furthermore, this was the only 2objects condition tested by Baylis and Driver (2001); only Baylis and Driver (1995) also tested 2objects-inner-sides and 1object-outer-sides conditions, see Figure 1. Baylis and Driver (1995) found that symmetry detection was much harder when contour polarity mismatched (for anti-symmetry, 2objects-right-sides stimuli, compared to true-symmetry, 2objects-inner-sides stimuli, see their Experiments 1 and 2). They also found that repetition detection was much harder when contour polarity mismatched (for anti-repetition, 2objects-inner-sides stimuli compared to true-repetition, 2objects-right-sides stimuli, see their Experiment 4). We expected to find similar results here, that would provide evidence for the importance of contour polarity for visual (as well as haptic) regularity detection.

5.4.1 Method

5.4.1.1 Participants

The same 24 participants who took part in Experiment 1 did Experiment 2 after a delay of 4-10 days (average 7 days). They all had normal or corrected to normal vision.

5.4.1.2 *Materials*

The vector files used to produce the stimuli used in Experiment 1 were re-used to create images that were presented on a computer monitor. The monitor had a resolution of 1920 x 1080 pixels and was placed in front of, and approximately 50cm away from, the participants' eyes. The top of the monitor was at approximately the same height as the top of the participant's head. Given the superior speed and accuracy of visual to haptic regularity detection, four times more trials were run in Experiment 2. In addition to the 240 stimuli used in Experiment 1, we created 240 more stimuli in the same way as in Experiment 1. These new stimuli were based on the 20 unique lines from Cecchetto and Lawson (2016) that were not used in Experiment 1. Every participant saw all 480 stimuli. The screen was black except for a centrally presented 12cm x 12cm background area of flickering noise. The noise consisted of squares of 2x2 pixels. About half of the squares were black and half were white with colour allocated at random on every frame. Objects were shown as bright green, solid surfaces (RGB: 0, 255, 0) against this background, see Figure 4. The stimuli displayed on the monitor were matched in size to the physical stimuli used in Experiment 1, so the 1object-outer-sides, 2objects-inner-sides and 2objects-right-sides stimuli were all 10cm high, and the two outer sides of the stimuli were, on average, 5cm, 10cm and 7.5cm apart respectively. Written prompts specifying how to respond were presented on the monitor whenever the stimuli were visible, see Figure 4.

5.4.1.3 *Design*

This was identical to Experiment 1 except that each block included 240 trials for a given regularity rather than only the 60 trials used in Experiment 1. Trials were presented in a different, random order for each participant. Participants did the same block order (symmetry then repetition or vice versa) as they had done in Experiment 1.

5.4.1.4 *Procedure*

This was identical to Experiment 1 except for the following points. Participants were instructed to centre their body midline to the centre of the

monitor. The experimenter then explained the task and showed the same physical practice objects as in Experiment 1. The experiment was run using PsychoPy software (Pierce, 2007). Each block of experimental trials was preceded by 10 practice trials that were taken from that block. These practice trials were the same for all participants and they included five regular and five irregular trials and a mixture of the three stimulus conditions. Participants were told to respond as quickly and accurately as possible using the keyboard by pressing 'S' for regular stimuli and 'K' for irregular stimuli. RT were recorded from the stimulus onset until the participant made a keypress response. At the start of each trial, a central fixation cross appeared on the monitor for 0.5s. This was replaced by the stimulus that remained on the monitor until the participant responded. Every 80 trials the experiment was paused and a visual prompt appeared on the screen inviting participants to take a break. Participants resumed the experiment by pressing 'G' on the keyboard. The experiment took about 30 minutes to complete.

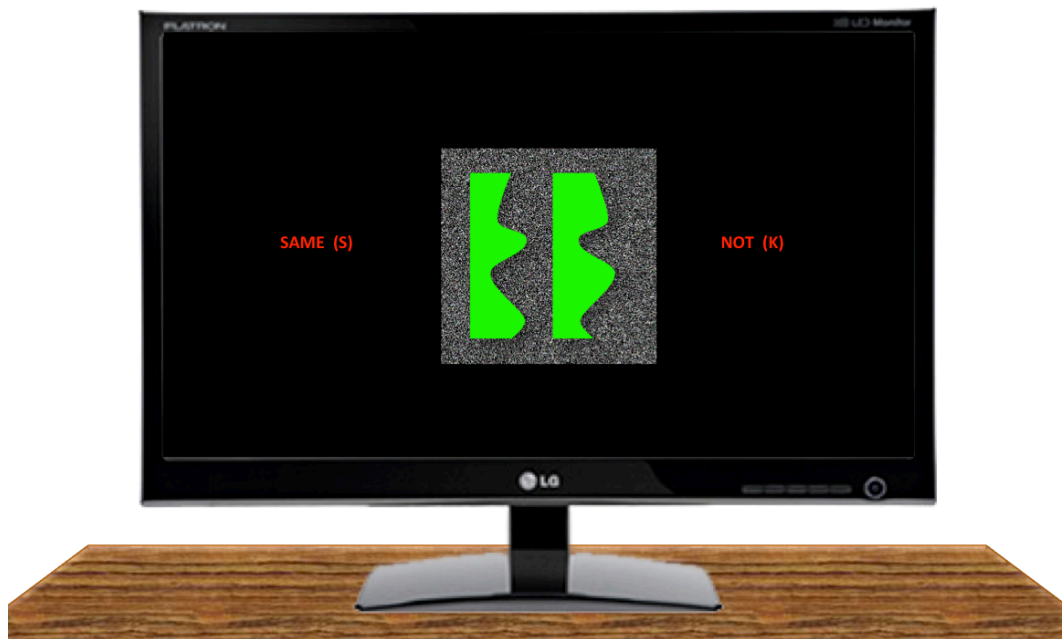


Figure 4. An example of a green, symmetrical, 2objects-right-sides stimulus surrounded by a background of flickering black and white noise set within a black frame, illustrating the set-up in Experiment 2. The text flanking the stimulus reminded participants to respond with the "S" key on regular trials and the "K" key on irregular trials.

5.4.2 Results

No participants were replaced. As in Experiment 1, 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. Correct RT faster than 0.45s or slower than 4.5s were discarded as outliers (less than 1.2% of trials). In the ANOVAs there were two within-participants factors: regularity-type (symmetry or repetition) and condition (1object-outer-sides, 2objects-inner-sides or 2objects-right-sides). All pairwise differences noted below were significant ($p < .05$) in post-hoc Newman-Keuls analyses. Appendix 2 gives the full ANOVAs for RT, errors and sensitivity (d'). Here, we focus on the theoretically important effects so we only report the results for the interaction of regularity-type \times condition and the results for the two critical comparisons.

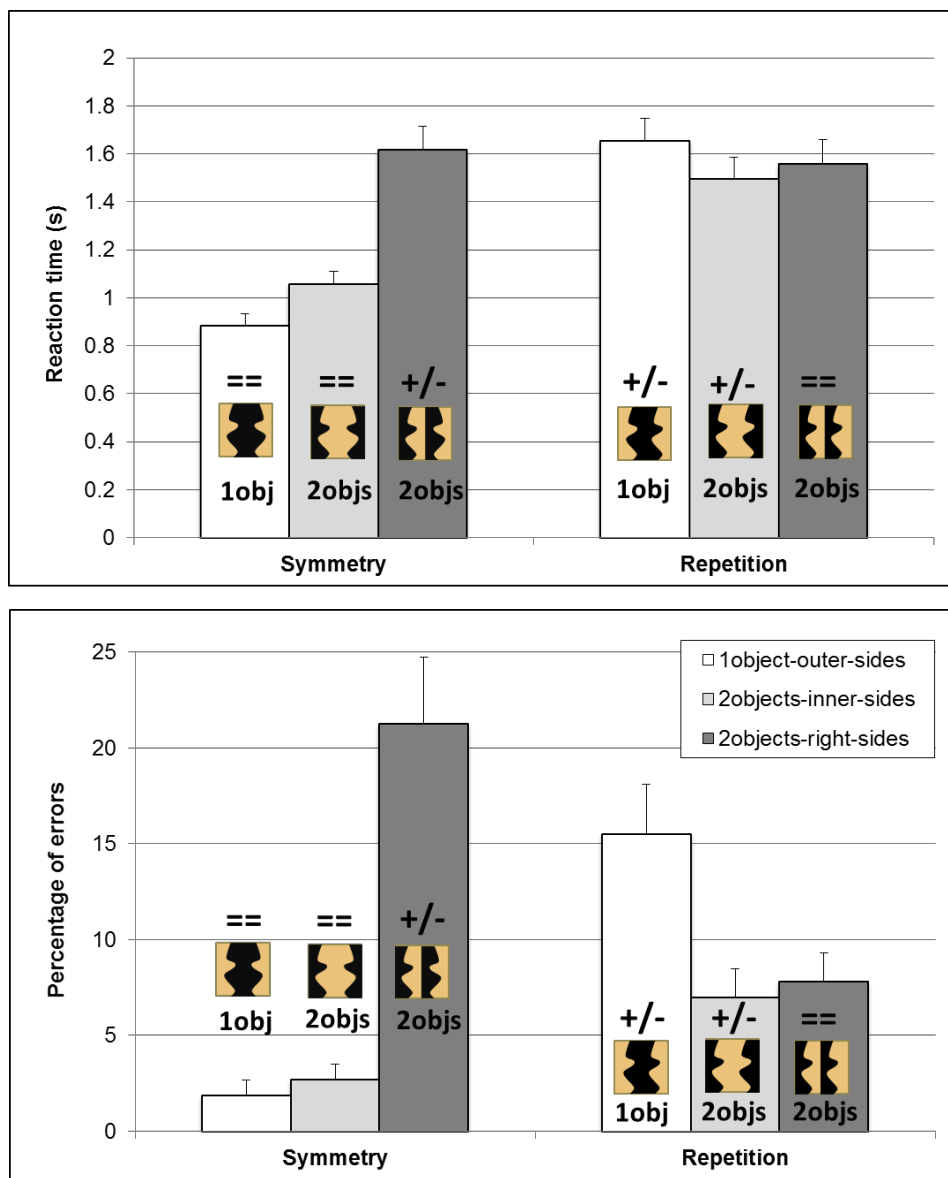


Figure 5. Results in Experiment 2, for regular trials, for the visual detection of symmetry and repetition, for 1object-outer-sides (white bars), 2objects-inner-sides (light grey bars) and 2objects-right-sides stimuli (dark grey bars), for RT (top), and errors (bottom). Error bars represent one standard error of the mean. Example stimuli from each condition are shown on or above each bar. For consistency with Figure 3, these stimuli show a black object against a light brown background, but note that in Experiment 2 the objects were actually green and the background was black and white noise, see Figure 4. Above each example stimulus, symbols indicate whether contour polarity across the pairs of critical contours matched (==) or mismatched (+/-). Below each example stimulus, the labels "1obj" and "2objs" indicate whether the critical

contours both belonged to a single object or each belonged to a different object respectively.

The interaction of regularity-type x condition was significant for RT [$F(2,46)=61.02, p < .001, \text{partial } \eta^2 = .73$], errors [$F(2,46) = 31.49, p < .001, \text{partial } \eta^2 = .58$] and sensitivity [$F(2,46) = 59.25, p < .001, \text{partial } \eta^2 = .72$], see Figure 5.

First, we considered whether variation in objectness influenced visual regularity detection when contour polarity was held constant, by comparing performance for 1object-outer-sides stimuli to 2objects-inner-sides stimuli. For true-symmetry detection, 1object-outer-sides stimuli (0.88s, 2%, d' of 3.79) were detected faster (though no more accurately or more sensitively) than 2objects-inner-sides stimuli (1.06s, 3%, 3.53). In contrast, for anti-repetition detection, 1object-outer-sides stimuli (1.65s, 16%, d' of 2.48) were detected slower and less accurately (though not significantly less sensitively) than 2objects-inner-sides stimuli (1.50s, 7%, 2.73). Thus, there were opposite effects of objectness for detecting symmetry (where there was a 1object advantage) and repetition (where there was a 2objects advantage).

Second, we investigated whether contour polarity influenced visual regularity detection when objectness was held constant, by comparing performance for 2objects-inner-sides stimuli to 2objects-right-sides stimuli. True-symmetry, 2objects-inner-sides stimuli (1.06s, 3%, 3.53) were detected faster, more accurately and more sensitively than anti-symmetry, 2objects-right-sides stimuli (1.62s, 21%, 2.18). Anti-repetition, 2objects-inner-sides stimuli (1.50s, 7%, 2.73) were detected less sensitively (but not significantly slower or less accurately) than true-repetition, 2objects-right-sides stimuli (1.56s, 8%, 3.13). Thus, for symmetry, true-regularities were substantially easier to detect than anti-regularities. In contrast, for repetition, the advantage for truly-regular over anti-regular stimuli only occurred for sensitivity and the effect there was only modest.

5.4.3 Discussion

In Experiment 2, the same types of closed-contour, planar shapes were presented to the same participants, in the same task as in Experiment 1, but

visual rather than haptic regularity detection was tested. We again compared the detection of true-regularities and anti-regularities for 1object and 2objects stimuli in order to investigate the role of contour polarity and objectness in the perception of symmetry and repetition.

First, visual regularity detection was influenced by objectness when contour polarity was held constant. Crucially, objectness had the opposite effect on symmetry versus repetition detection, with a 1object advantage for symmetry detection but a 2objects advantage for repetition detection, see Figure 5, consistent with previous results for vision. The exact nature of this objectness and regularity-type interaction has varied across previous studies of visual regularity detection (Koning & Wagemans, 2009). However, in general, symmetry has shown a 1object advantage whilst repetition has shown a 2objects advantage, consistent with what we found here. These results contrast to previous results for haptics, including Experiment 1 here, as well as Cecchetto and Lawson (2016) and Lawson et al., (2016), which have found no 2objects advantage for repetition detection and no objectness and regularity-type interaction.

Second, we investigated the role of contour polarity when objectness was held constant. As for haptics, the visual detection of true-regularities was easier than that of anti-regularities, see Figure 5. However, unlike haptics, this cost differed substantially depending on the type of regularity being tested. Visual detection was much harder for anti-symmetry than true-symmetry, whereas there was only a modest cost (and for sensitivity only) for visually detecting anti-repetition compared to true-repetition.

These two findings replicated the pattern of results obtained by Baylis and Driver (1995), who tested visual symmetry detection and visual repetition detection in separate experiments (Experiments 1 and 4 respectively). Keeping contour polarity constant, they found a 1object advantage for symmetry detection and a 2objects advantage for repetition detection with modest effects in both cases (~30-40ms for RT, ~2% on errors for regular trials). Keeping objectness constant, they found true-symmetry was much easier to detect than anti-symmetry (>200ms on RT, ~10% on errors for regular trials) whilst true-repetition was somewhat easier to detect than anti-repetition (~30-40ms on RT, ~2% on errors for regular trials). Thus, consistent with our results from

Experiment 2, Baylis and Driver (1995) observed objectness effects in opposite directions for symmetry versus repetition detection and a greater cost for detecting anti-regularities for symmetry than for repetition. In the General Discussion, we return to consider the reasons for these differences between the visual detection of symmetry versus repetition.

5.5 General Discussion

We investigated the detection of regularities for closed-contour, planar shapes by haptics (Experiment 1) and vision (Experiment 2). The same participants were shown similar sets of stimuli in both modalities. We varied objectness¹, comparing performance for 1object and 2objects stimuli, and we varied contour polarity, comparing the detection of true-regularities to anti-regularities.

We obtained quite similar results for the detection of symmetry across haptics and vision whereas we found a clear difference between the modalities for the detection of repetition. As elaborated below, we suggest that the effects of objectness (comparing whether pairs of critical contours belonged to opposite sides of a single object, or to the sides of two different objects) and of contour polarity (comparing matched, to mismatched, sets of concavities and convexities along pairs of critical contours) differed across the two modalities. This, in turn, suggests that modality-specific differences in perceptual encoding and processing have powerful effects on regularity detection. These results provide further support for our general claim that human object perception is highly sensitive to how we acquire and process information. As a consequence, effects on regularity detection do not just reflect our perceptual system inferring information from differences in the distribution of symmetry and repetition in our physical environment since the presence of any such externally generated cues should be modality-independent (Cecchetto & Lawson, 2016; Lawson et al., 2016).

For *symmetry* detection, both haptics and vision showed a greater sensitivity to contour polarity (comparing 2objects-inner-side to 2objects-right-side stimuli, where objectness was held constant) than to objectness (comparing 1object-outer-side to 2objects-inner-side stimuli, where contour polarity was held constant). Anti-symmetry (with mismatched contour

polarities) was much harder to detect than true-symmetry (with matched concavities and convexities). Indeed, for haptics, performance was worse than chance at detecting anti-symmetry (see Figure 3). For vision, performance was better but anti-symmetry was still much harder to detect than true-symmetry (see Figure 5). In contrast, there were no objectness effects for haptic true-symmetry detection, and there was only a modest 1object advantage for only the speed of visual true-symmetry detection.

For *repetition* detection, haptics showed greater sensitivity to contour polarity than to objectness, with performance similar to that of both haptic and visual symmetry detection. Haptically, anti-repetition was much harder to detect than true-repetition (see Figure 3) whilst there was a modest 1object advantage for detecting anti-repetition. In contrast, visual repetition detection showed a very different pattern. First, there was little effect of varying contour polarity, with no cost on speed and only a modest cost on sensitivity for detecting anti-repetition compared to true-repetition (see Figure 5). Second, there was a clear effect of objectness which was in the opposite direction to all other conditions, with a 2objects advantage for visual repetition detection.

The present results, in combination with related studies (Cecchetto & Lawson, 2016; Lawson et al., 2016), have examined the effects of a number of visual and haptic cues to try to specify which cues are important for defining what is an object for each modality. This is an ambitious topic to tackle, given that it has proven difficult to provide a formal definition of objectness even for vision (Feldman, 2013), whilst for haptics we are not aware that this topic has even been discussed before. Other studies that have investigated the effects of objectness on regularity detection (e.g., Baylis & Driver, 1995, 2001; Bertamini et al., 1997; Bertamini, 2010; Corballis & Roldan, 1974; Koning & Wagemans, 2009; Treder & van der Helm, 2007) have not usually considered what defines an object and they have tried to distinguish 1object from 2objects stimuli using a diverse range of visual cues (e.g., contour closure, colour, luminance, type of regularity, stratification in depth, and line and dot separation). In many cases, these manipulations, in turn, introduced confounds such that 1object and 2objects stimuli differed in respects other than objectness and these differences could also play a role in shape perception. For example, as noted by van der Helm and Treder (2009), contour polarity often matched in some conditions

(producing true-regularities) but mismatched in others (producing anti-regularities).

This difficulty in producing stimuli to use to independently test the effects of objectness and contour polarity means that no single approach is likely to allow watertight conclusions to be drawn about the role of each factor. Given this, we argue that the best approach is to attempt to find converging evidence by systematically varying a series of different factors, including using different modalities, different tasks, different modes of exploration and different stimuli. This was our aim in the present experiments, which comprise a subset from a series of companion studies (Cecchetto & Lawson, 2016; Lawson et al., 2016).

We propose that one factor that may be particularly important for detecting haptic regularities and for haptically defining objects is the manner of stimulus exploration. There has been some work on the effects of exploration and the manner of information extraction for vision, for example investigating how eye movements influence shape perception for 3D objects (e.g., Leek, Cristino, Conlan, Patterson, Rodriguez & Johnston, 2012). For haptics, we have found that varying whether one hand or two hands are used to feel stimuli influences the detection of regularities (Cecchetto & Lawson, 2016; Lawson et al., 2016). In Experiment 1 here, participants always used the index fingers of their right and left hands to explore the right and left critical contours respectively, so the gross hand movements involved were consistent across conditions. Nevertheless, we believe that different modes of exploration may have been used for the three stimulus conditions, based on our informal observation of participants as they did the task (see Figure 6). In particular, regardless of the nature of the regularity being detected, the 3D structure of the stimuli encouraged the fingertips to be directed at different orientations, as indicated by the red arrows shown in Figure 6. These directions were symmetrically convergent, symmetrically divergent or repeatedly parallel during the exploration of 1object-outer-sides, 2objects-inner-sides and 2objects-right-sides stimuli respectively. These stimulus-driven differences in the mode of haptic exploration may have enhanced effects of contour polarity for haptic relative to visual regularity detection. We suggest that regularity detection was easy when the nature of the regularity being detected (symmetry versus repetition) was congruent with the type of exploration used

for a given type of stimulus (symmetrically convergent or divergent versus repeatedly parallel respectively). In future research we intend testing this hypothesis directly, by requiring participants to feel contours from a particular direction, in order to manipulate whether symmetrical or repeated exploration occurs. If changing the manner of exploration does not alter task performance it would suggest that the effects reported here, in Experiment 1, depended solely on the contour polarity of the stimuli. However, if regularity detection for symmetry, versus for repetition, is influenced by whether stimuli are explored symmetrically or repetitively this would provide further evidence that the nature of exploration influences the representation of shape by haptics. This, in turn, would support our general claim that human regularity detection depends on how we acquire and process information rather than only reflecting universal, modality-independent properties of our external, physical world.

In conclusion, our results showed that for symmetry detection, the cost of having mismatching contour polarity (anti-symmetry) outweighs the 2objects cost for both modalities. For repetition detection, the cost of having mismatching contour polarity (anti-repetition) outweighs the 2objects cost for haptics. However, the results are very different for vision. Here, there is a 1object cost and this outweighs the cost of having mismatching contour polarity (anti-repetition). We suggest that both vision and haptics use multiple cues to determine the presence and location of objects, with the cues used, and their relative importance, differing across vision and haptics (see Figure 6). We further speculate that differences in how our hands feel the edges of shapes may explain why contour polarity is so important for haptics. Overall, our conclusions are consistent with our more general claim that the many modality-specific differences in regularity detection across vision and haptics suggest that how we perceive symmetry and repetition revealing how we extract and use information, rather than only reflecting what physical information is available in our environment.

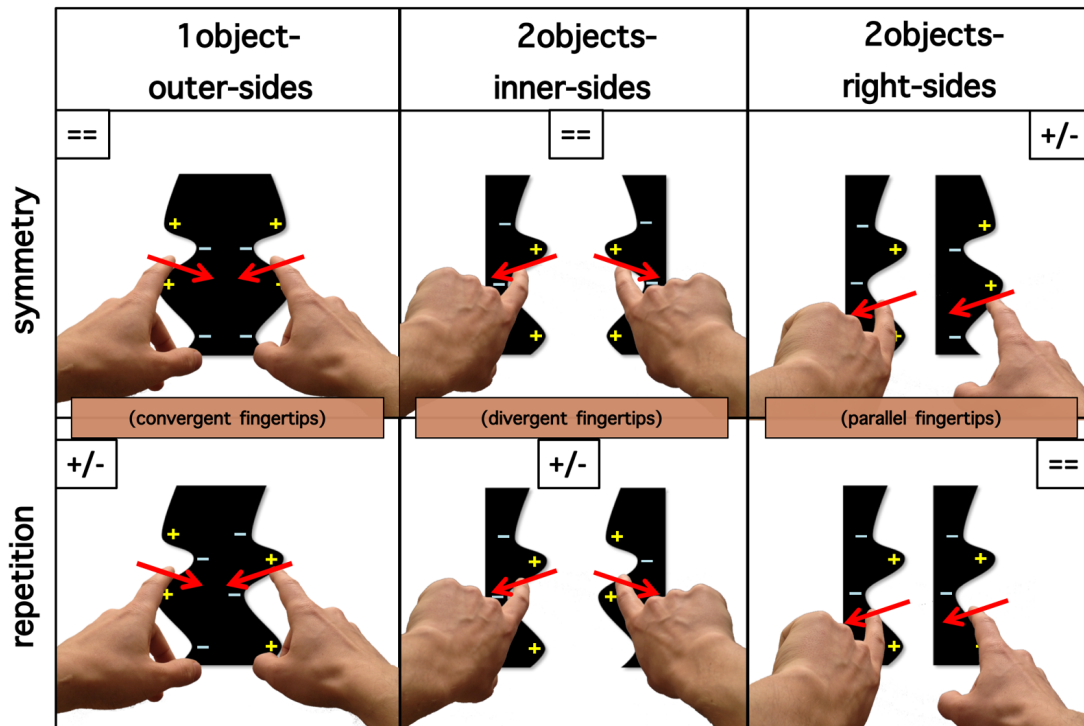


Figure 6. Illustration of how the six different conditions for regular stimuli tested in Experiment 1 might be explored haptically. Objects are shown as black, closed-contour shapes against a white background. For 1 object-outer-side stimuli (first column) and 2 objects-inner-sides stimuli (second column), symmetry detection might be easier than repetition detection due to the manner of exploration. Symmetrical stimuli would be explored symmetrically, using either convergent or divergent movements (i.e., pressing the fingers together or pushing the fingers apart respectively, see the red arrows). In contrast, the nature of exploration (i.e., symmetrical) would mismatch with the type of regularity to be detected for repeated stimuli. For 2 objects-right-sides stimuli (third column), the reverse pattern would be expected. Here, repetition detection might be easier than symmetry detection because people would move their fingers in tandem to explore these stimuli, using repeated, parallel movements.

Footnotes

1 In this study, participants were told which regions they should interpret as objects, and which as background. Participants may, though, have undertaken a figure-ground reversal. For example, the 2 objects-inner-side stimuli may have been perceived with the central background region as the

object flanked by two background regions, such that they were interpreted in the same way as the 1object-outer-side stimuli. However, two pieces of evidence point against this possibility. First, in several cases performance differed significantly across these two conditions indicating that people interpreted them differently. For example, see Figure 3 for the speed of haptic repetition detection, and see Figure 5 for the speed of visual symmetry detection and the speed and accuracy of visual repetition detection. Second, in a symmetry detection task, Baylis and Driver (1995, Experiment 3) manipulated only the instructions to participants in order to assign whether red surfaces were to be interpreted as figure and green surfaces as background, or vice versa. They found a different pattern of performance for physically identical stimuli depending on whether people were told that the red or the green surfaces represented objects. Thus, in their study, people did follow their instructions about what represents an object. In the present study, our participants were likely to have followed their instructions because there were salient physical differences between the figure and the background regions that reduced the ambiguity of figure-ground assignment. In Experiment 1, this was achieved by using 3D objects that were raised above the background surface, with participants being shown visual examples of the stimuli before they began the experiment. In Experiment 2, participants had already completed Experiment 1 and so were familiar with the stimuli. In addition, they were again shown visual examples of the 3D, physical versions of the stimuli before they began the experiment (which presented images on a monitor, see Figure 4). Finally, during Experiment 2 the background consisted of flickering noise whilst the object was defined by a smooth, solid surface.

Chapter 6

6 Revealing regularity detection over time: Making visual perception more like haptic perception using a touch-guided, moving aperture

* This study is in preparation for submission as: Lawson, R. & Cecchetto, S. Revealing regularity detection over time: Making visual perception more like haptic perception using a touch-guided, moving aperture. (In preparation)

6.1 Abstract

A major issue in perception is whether results from behavioural studies reflect intrinsic properties of the environment or the way in which observers process that information. Vision and haptics are both able to extract regularities and shape information efficiently so the processes involved here can be used to investigate this issue. If effects on symmetry and repetition detection reflect intrinsic attributes of the environment, then we would expect the same pattern of results from both modalities. Contrary to this prediction, Cecchetto and Lawson (in press) found evidence for modality-specific effects on regularity detection. For vision they obtained a one-object advantage for symmetry detection and a two-objects advantage for repetition detection whereas for haptics they found a one-object advantage for detecting both symmetry and repetition. The present study tried to understand why these differences occurred by investigating visual regularity detection when stimuli processing was more like haptic processing. Across three studies we manipulated whether stimuli were explored serially, using an aperture, rather than being

presented simultaneously. Aperture position was controlled by the participant's hand movements using a separate touchscreen. Visual regularity detection with serial exploration was more like that of haptics, with no two-object advantage for detecting repetition. Furthermore, complexity effects on regularity detection were eliminated for serially explored stimuli. Our findings point to the importance of the manner of exploration for perception. They support the claim that effects on regularity detection reflect how stimulus information is acquired by a given modality, rather than reflecting necessary properties of that modality.

6.2 Introduction

Visual regularities are commonplace in our world. Bilateral mirror-reflections (henceforth termed symmetry) and repeated contours which have been translated (henceforth termed repetition) are two important regularities that our visual system uses to structure the information that we perceive into meaningful elements (Palmer, 1983; Wagemans, 1995). Many of the most important objects to us, such as people, animals and tools, have symmetrical contours, whilst we often see repetition contours when multiple, similarly shaped objects are near to each other and aligned (see Figure 1). The ubiquity and salience of symmetry has led to considerable research efforts into understanding how and why symmetry is detected so efficiently (for reviews, see Treder, 2010; Tyler, 1995; Wagemans, 1995, 1997). More recently, studies have compared symmetry to repetition detection (e.g., Baylis & Driver, 1994, 1995, 2001; Bertamini, FriedenberG & Kubovy, 1997; Cecchetto & Lawson, in press; Koning & Wagemans, 2009; Lawson, Ajvani & Cecchetto, in press) as a means of investigating whether different types of regularity are used by our perceptual system as cues to signal different properties in the world (Koning & Wagemans, 2009; Treder & van der Helm, 2007; van der Helm & Treder, 2009). In particular, it has often been proposed that symmetry may signal the presence of a single, bilaterally symmetric object, whilst repetition may signal the presence of multiple objects (see Figure 2). This hypothesis has been supported by a number of studies that have reported an interaction between regularity-type and objectness (e.g., Baylis & Driver, 1995; Bertamini et al.,

1997; Bertamini, 2010; Cecchetto & Lawson, in press; Koning & Wagemans, 2009; Lawson et al., in press). In the most clear-cut findings (e.g., Koning & Wagemans, 2009), symmetry is easier to detect when it is a property of one-object compared to two-objects stimuli, with the reverse effect for repetition. Koning and Wagemans (2009) proposed that intrinsic properties of visual processing (driven by structural differences between stimuli) underlay the one-object advantage for symmetry and the two-objects advantage for repetition.



Figure 1. Examples of symmetry and repetition in everyday life. From top left, a repeated set of symmetrical glasses, stone columns (<https://pixabay.com/it/colonne>

colonnine-pietre-simmetria-596406/) and *amphitheatre steps* (<https://pixabay.com/it/anfiteatro-lione-costruzione-1004396>).

Recently, we have tested whether Koning and Wagemans' (2009) conclusions about visual regularity detection generalised to detecting symmetry and repetition in a different modality, namely haptics, which is our sense of active touch (Cecchetto & Lawson, in press; Cecchetto & Lawson, in preparation; Lawson et al., in press). Like vision, haptics is specialised at extracting shape information, and there are many similarities in how the two modalities identify objects and their properties. Across a number of studies, we have compared the ability of vision and haptics to detect regularities using the same tasks and stimuli (e.g., Craddock & Lawson, 2009a, Lawson, 2009; Martinovic, Lawson & Craddock, 2012). Recently we have directly investigated the interaction between regularity-type and objectness for vision and touch (Cecchetto & Lawson, in press).

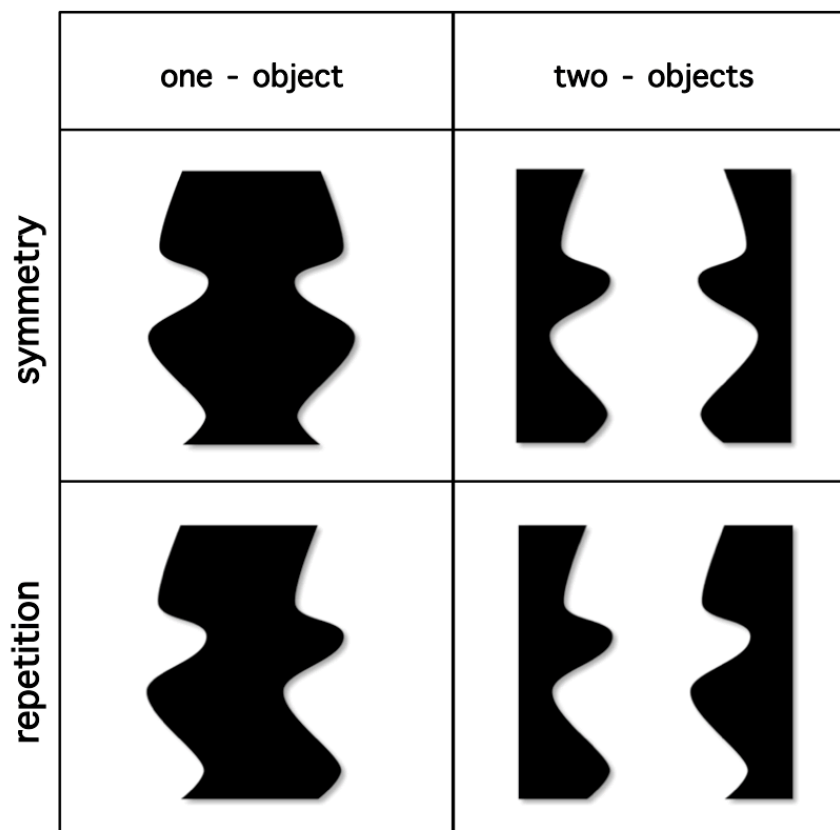


Figure 2. An example of regular, one-object (left column) and two-objects (right column) stimuli showing symmetry (top row) and repetition (bottom row). These regularities were specified with respect to the pairs of critical, vertical contours which

comprised either the two sides of one-object stimuli or the facing sides of two-objects stimuli. Csathó, van der Vloed & van der Helm (2003) and van der Helm and Treder (2009) have argued that the stimuli on the bottom row should be described as anti-repetition rather than true-repetition stimuli since the critical pair of repetition contours have opposite polarities in terms of concavities and convexities, and in terms of colour and luminance with respect to the figure relative to its background. In other work we have discussed this issue (Lawson et al., in press) and we have compared the detection of true-regularities and anti-regularities (Cecchetto & Lawson, in preparation).

For vision we replicated the finding of an interaction between regularity-type and objectness reported by Koning and Wagemans (2009; see also Baylis & Driver, 1995; Bertamini et al., 1997). In contrast, for haptics, we found no such interaction. Instead, 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 exploration with two hands. These modality-specific differences in the effects of objectness provide evidence against the claim that regularity detection reflects only external properties of our physical environment, since in our studies the same 3D objects generated the stimuli for vision and touch. We argued that these results may be informing us about differences in processing across our sensory systems. Specifically, the way our senses explore the world to acquire information might be crucial for explaining these differences. This hypothesis was investigated further in the present study.

In the first experiment, we investigated whether forcing visual exploration of a stimulus to be serial, rather than presenting the whole stimulus simultaneously, would increase the similarity of regularity detection across the two modalities, since haptic exploration is largely serial. To achieve this, we used aperture viewing. Participants saw a stimulus behind a narrow, horizontal aperture so that their field-of-view was restricted to just one small parts of the stimulus at any time (see Figure 3). They used their right hand on a separate touchscreen to move the aperture up and down so they could, nevertheless, explore the entirety of the stimulus. Other studies have also tried to serialize vision in order to make visual and haptic perception more similar (e.g., Ruotolo, Ruggiero, Vinciguerra & Iachini, 2012). We are able to integrate information over time in order to perceive objects seen behind apertures as

unified wholes (Craddock, Martinovic & Lawson, 2011; Loomis, Klatzky & Lederman, 1991; Morgan, Findlay & Watt, 1982; Parks, 1965). Furthermore, aperture viewing has already been used to compare visual to haptic perception. For example, Loomis et al. (1991) reported that constraining the visual field-of-view to the width of a fingertip resulted in the recognition of raised line drawings by vision being as slow as for haptics. Similarly, both Martinovic et al. (2012) and Craddock, Martinovic and Lawson (2011) used aperture viewing to slow visual responses to a similar speed to that of haptics in an object familiarity task.

The second experiment varied whether stimuli were explored serially or were presented simultaneously and also varied stimulus complexity. A similar complexity manipulation was used by Baylis and Driver (1994, 2001). This involved varying the number of discontinuities along each critical contour for 2D planar stimuli. Baylis and Driver (1994, 2001) found that symmetry detection for one-object stimuli was not affected by complexity whereas repetition detection was. They proposed that this result arose because symmetry within an object can be detected across the whole stimulus simultaneously, whereas repetition must be processed serially, by a series of effortful and time-consuming pairwise comparisons of each discontinuity along the two critical contours. We followed the design of the visual regularity detection studies conducted by Baylis and Driver (1994, 2001) which involved presenting stimuli simultaneously and we then compared performance on this task to performance with serially explored stimuli, using the same aperture paradigm used in Experiment 1. We predicted that increasing stimulus complexity would make repetition detection harder but would not affect symmetry detection for simultaneous presentation, which would replicate the results of by Baylis and Driver (1994, 2001). In contrast, for serial exploration we expected to find the detection of both symmetry and repetition would be harder for more complex stimuli and that people would perform similarly for symmetry detection and repetition detection.

In the third, and final, experiment we investigated whether restricting the presentation duration for simultaneously presented stimuli would harm repetition detection more than symmetry detection whereas allowing

unlimited viewing of stimuli would reduce the difference between detecting repetition and symmetry.

In summary, across three visual regularity detection experiments we investigated the role of exploration in the perception of shape. We hypothesized that the different pattern of results that we previously obtained for the visual and haptic detection of symmetry and repetition (Cecchetto & Lawson, in press) was a consequence of the different way in which the two modalities explored stimuli and acquired information about them. We tried to make the visual acquisition of information more like that of haptics by using apertures to serialise visual exploration in Experiment 1 and we re-examined the regularity-type by objectness interaction that has previously been reported. We compared regularity detection for one-object stimuli only that were explored serially or were presented simultaneously in Experiment 2, and we also varied stimulus complexity. Finally, we varied whether simultaneously presented stimuli were shown briefly or for an unlimited duration in Experiment 3.

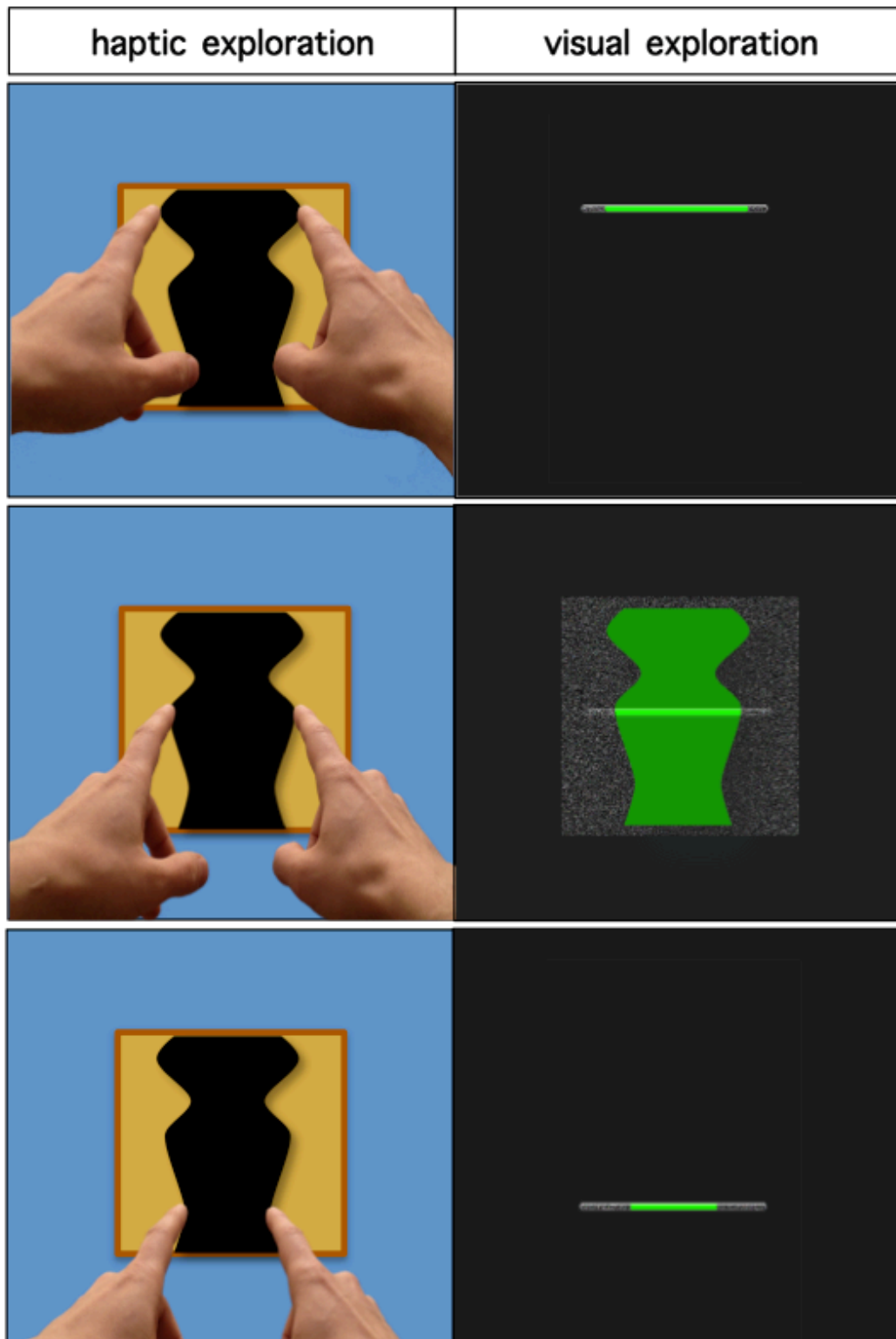


Figure 3. Illustration of the aperture-viewing manipulation used to permit serial exploration of visual stimuli in Experiments 1 and 2. In order to approximate the serial time-course and restricted field-of-view of haptic stimulus exploration using two index fingers (as shown in the left column, with a symmetrical, one-object stimulus, for

stimuli similar to those used in Cecchetto & Lawson, in press), in the current study we created digital versions of the original haptic stimuli and presented them visually behind a movable aperture (shown in the right column). The aperture revealed only a small portion of the green visual stimulus and the background black and white noise surrounding it at a time. Participants moved their right index finger on a touchscreen to control the vertical position of the aperture. The figure illustrates three phases of exploration, from top to bottom. For illustrative purposes only, the middle right illustration shows a partly-transparent aperture in order to reveal the entirety of the stimulus underneath. Note that only visual (not haptic) stimuli were presented in the current study.

6.3 Experiment 1

Vision can typically extract shape information fast and simultaneously across the whole stimulus. In contrast, haptics typically extracts information in a slow, serial manner, such that information must be integrated from contact with a succession of separate areas of an object (Craddock et al., 2011; Lederman & Klatzky, 1987; Lakatos & Marks, 1999; Martinovic et al., 2012). In Experiment 1, we investigated whether forcing serial exploration of visual stimuli, using an aperture, would eliminate the interaction between regularity-type and objectness that we have found for visual regularity detection when the whole stimulus was shown simultaneously (Cecchetto & Lawson, in press; see also Koning & Wagemans, 2009; Lawson et al., in press). We found no interaction between regularity-type and objectness for haptic regularity detection where participants typically explore stimuli serially by tracing their fingers along the critical contours. In particular, we never observed a two-objects advantage for haptic repetition detection whereas we have always obtained a clear two-objects advantage for visual repetition detection (Cecchetto & Lawson, in press).

Participants viewed 2D novel stimuli through a narrow, moveable horizontal aperture so they could only see a small parts of the stimulus at a time. The vertical position of the aperture was actively controlled by the participants moving their right index finger up and down on a separate touchscreen. Their task was to discriminate symmetrical from irregular stimuli, and repetition from irregular stimuli, in separate blocks. The two

critical contours on each trial could either belong to one single object or to two separate objects, see Figure 4. We predicted that if effects on regularity detection reflect how our sensory systems extract and process information then aperture viewing should make visual regularity detection more similar to haptic regularity detection. If so, then we would expect an overall advantage for symmetry detection but no interaction with objectness, replicating the results of Cecchetto and Lawson (in press).

6.3.1 Method

6.3.1.1 Participants

Twenty-four students from the University of Liverpool (13 females, mean age = 22.3 years, s.d. = 5, range 18-36) took part in Experiment 1, with most receiving course credit. All participants declared having normal or corrected-to-normal vision and self-reported as right handed. All of the experiments reported here received ethical approval from the local ethics committee of the University of Liverpool.

6.3.1.2 Materials

A set of 320 stimuli was created using Inkscape. Each stimulus fitted into a background square of 10cm x 10cm. The stimuli were identical to the visual stimuli used by Cecchetto and Lawson (in preparation) and were similar in to those used by Cecchetto and Lawson (in press) except that the vertices were rounded. Each stimulus was based on one of 40 unique, vertically aligned lines, each of which had four vertices. The top and bottom of the unique line was placed 2.5cm from the left edge of the background square to create the left critical contour. For the repetition stimuli, a copy of this left critical contour was translated to the right by 5cm to create the right critical contour. The top and bottom of this contour was thus 2.5cm from the right edge of the background square. Matched points along pairs of repetition critical contours were thus always 5cm apart. Irregular stimuli were created in the same way as these regular repetition stimuli except that the right critical

contour was replaced by a different unique line (see Cecchetto & Lawson, in press, and Cecchetto & Lawson, in preparation, for details). Each of these 40 regular repetition and 40 irregular stimuli were then used to create the 40 regular symmetrical stimuli and 40 irregular stimuli respectively by reflecting the right critical contour about its midline.

Once the 160 pairs of critical contours had been created the one-object stimuli were produced by filling the space between the two critical contours with a solid green colour (RGB = 0, 255, 0) and the remaining area of the background square with random, flickering black and white noise. The noise consisted of black or white 2x2 pixel squares which were positioned at random and which moved position on each frame. The squares moved by 10 pixels horizontally and 150 pixels vertically on each frame. The two-objects stimuli were created from the one-object stimuli by replacing the visual noise with green and the green with visual noise. Finally, the background square was surrounded by a 1cm wide border of visual noise created in the same way as described above to give a total area of 12cm x 12cm, see Figure 4.

Using Psychopy (Peirce, 2007) we presented stimuli on an LCD 3D monitor (50cm x 40cm with a diagonal of 58cm and a resolution of 1920 x 1080 pixels). A stereo disparity of 20 pixels was added between the stimuli (which had zero disparity) and the noise background (which appeared to lie behind the monitor surface) so the stimuli were perceived as floating in front of the background. Finally, most of the stimuli and background were obscured by a black mask at zero disparity. To present the stimuli stereoscopically, two polarized images were displayed, superimposed, on the monitor. Observers wore 3D passive glasses with polarized filters so each eye saw a different, polarized image. The stimuli and background were only visible through a narrow aperture (12cm wide, 0.5cm high) in the black mask. The height of the aperture was controlled by movements of the right hand using an external 33.7cm x 27cm touchscreen (ELO Touchsystems, USA), see Figure 5, which was used as a large trackpad. The stimulus and background positions were fixed throughout each trial with only the aperture location changing.

Each participant was tested individually in a quiet, dimly lit laboratory. They sat about 60cm in front of the monitor. The height of the chair was adjusted so that the participant's head was about level with the midpoint of the monitor. The keyboard was on their left and the touchscreen, which was

horizontally oriented, was on their right, see Figure 5. The lower parts of the touchscreen was covered by cardboard (33.7cm x 15cm) so that participants could only touch the top 12cm so this height matched that of the stimulus.

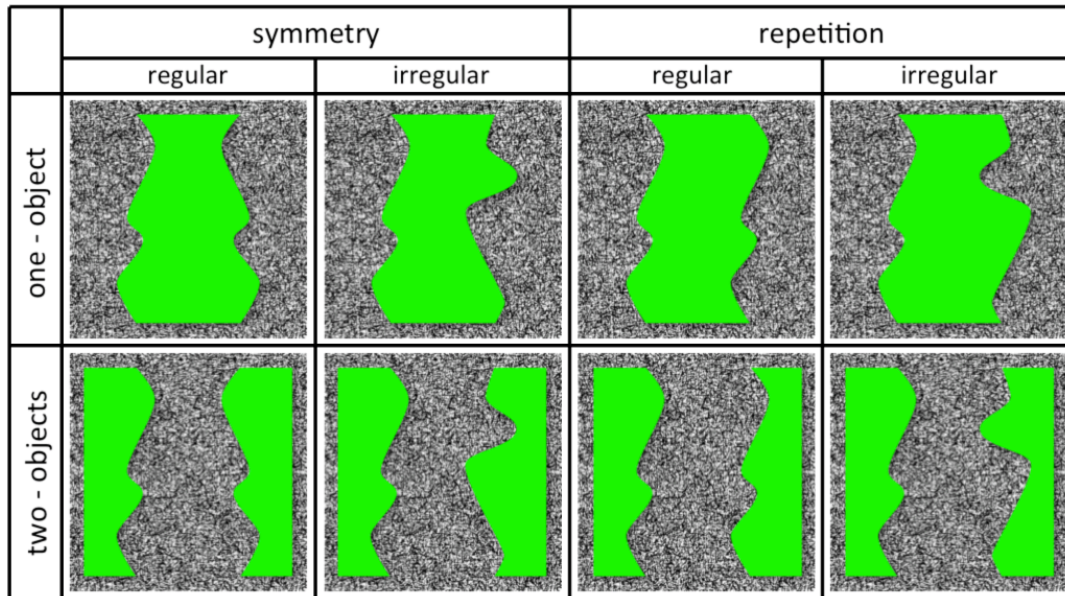


Figure 4. The eight stimuli created from a single unique line (in this example, unique line 38). The objects were coloured bright green and the background was random, flickering black and white squares. The full stimuli are shown here but in Experiment 1 participants only saw a small parts of the stimulus through a horizontal aperture (see Figures 3 and 5).

6.3.1.3 Design and Procedure

Participants did one block of 160 symmetry detection trials and one block of 160 repetition detection trials. Block order was counterbalanced across participants. Each block included 80 one-object trials (40 regular and 40 irregular) and 80 two-objects trials (40 regular and 40 irregular). All 320 stimuli were presented once to each participant across the two blocks. Participants did the trials in a different, random order within each block.

To explain the task, participants were first told about the nature of the regularity they were about to detect (symmetry or repetition). They were then shown laser-cut, 3D examples of the types of shapes that they would be seeing and they were told to attend to the pairs of critical contours. They then put on

the 3D passive glasses and were shown five further example stimuli on the monitor. These practise trials were taken at random from the experimental trials and were displayed behind a partly-transparent mask (20% transparency). Participants could see all of the stimulus whilst they practised using the touchscreen to move the aperture. Finally, participants completed 10 practice trials which were again selected at random from the experimental set. Here the mask was fully opaque (0% transparency) so the stimulus was only visible through the aperture.

Instructions on the monitor told the participants to swipe their right index finger up to the top edge of the touchscreen to start each trial by triggering presentation of the stimulus. This ensured that both their right index finger and the aperture always started from the same, uppermost position. Once the aperture appeared participants could freely move their finger down and up again to explore the stimulus for as long as they wanted until they made their response. Reaction times (RT) were recorded from the stimulus onset until their response. Participants pressed 'h' or 'k' on the keyboard using their left hand for regular and irregular stimuli respectively. Prompts reminding participants about how to respond remained on the monitor whilst the stimulus was displayed, see Figure 5. Participants were told to respond as fast and as accurately as possible. After responding, a high or low pitch sound was given as feedback to indicate a correct or wrong response respectively. The whole experiment lasted about 35 minutes.



Figure 5. A schematic illustration of the experimental setting of Experiment 1 shown from the participant's point of view. In this example, a small parts of a one-object stimulus (in green) surrounded by visual noise (black and white dots) is visible through the aperture. Participants could serially explore all of the stimulus by swiping their right index finger up and down along the uncovered (darker) area of the touchscreen in order to move the aperture on the monitor up and down respectively.

6.3.2 Results

Five participants were replaced because they performed poorly, making over 25% errors. Correct RT faster than 0.5s or exceeding 20s were removed as outliers (less than 1% of trials). ANOVAs were conducted on the mean correct RT and on the percentage of errors. A full analysis including all factors was performed for each experiment reported here but we will only discuss below the results for regular trials. This was done for consistency with our own previous studies and those of Koning and Wagemans (2009) and because it is difficult to theoretically interpret the results for irregular trials. There were two within-participants factors: regularity-type (symmetry or

repetition) and objectness (one-object or two-objects). All pairwise differences noted below were significant ($p < .05$) in post-hoc Newman-Keuls analyses.

Regularity-type was not significant for either RT $F(1,23) = 3.74, p < .07$, partial $\eta^2 = .14$] or errors [$F(1,23) = .60, p < .5$, partial $\eta^2 = .03$]. There was no difference between symmetry detection (4.06s, 11.4%) and repetition detection (3.47s, 10.4%); the trend was the reverse of that typically found, with repetition tending to be detected slightly faster than symmetry. Objectness was significant for both RT [$F(1,23) = 19.95, p < .001$, partial $\eta^2 = .46$] and errors [$F(1,23) = 18.83, p < .001$, partial $\eta^2 = .45$]. One-object stimuli (3.59s, 8.1%) were detected faster and more accurately than two-objects stimuli (3.94s, 13.6%). Finally the interaction of regularity-type \times objectness was significant for RT [$F(1,23) = 8.18, p < .009$, partial $\eta^2 = .26$] but not for errors [$F(1,23) = 1.75, p < .2$, partial $\eta^2 = .07$], see Figure 6. Symmetry detection was faster for one-object stimuli (3.80s, 7.7%) than two-objects stimuli (4.31s, 15.1%) whereas for repetition there was no significant difference between detecting one-object stimuli (3.37s, 8.5%) and two-objects stimuli (3.57s, 12.2%). The trend was for a one-object advantage for repetition, similar to symmetry detection. This contrasts to the powerful two-objects advantage for repetition detection which we have previously found for simultaneous visual presentation using similar stimuli and tasks (Cecchetto & Lawson, in press; see also Koning & Wagemans, 2009).

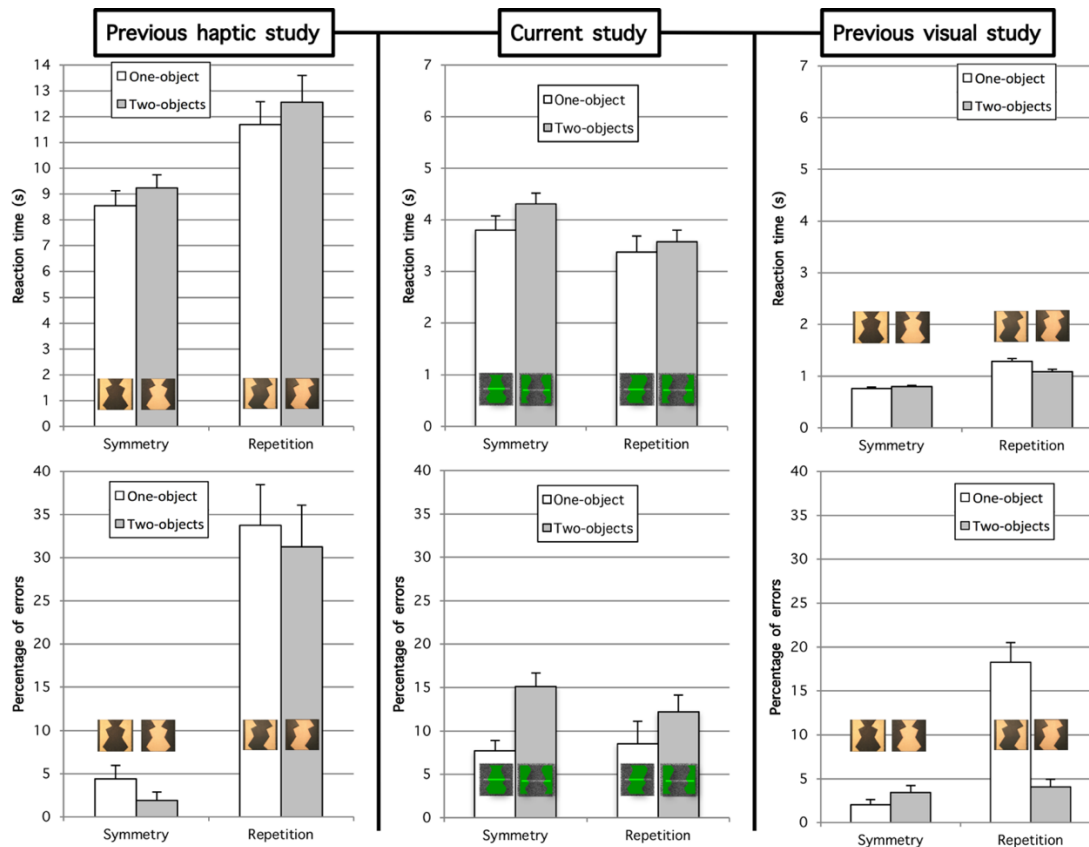


Figure 6. Results for regular trials for the detection of symmetry and repetition for one-object stimuli (white bars) and two-objects stimuli (grey bars) for RT (top; note that the scale differs for the left compared to the central and right graphs) and percentage errors (bottom). Results from (Experiment 1, central graphs) are shown next to results from previous haptic (left graphs) and visual (right graphs) regularity detection studies (Experiment 1 and 4 respectively from Cecchetto & Lawson, in press). Error bars represent one standard error of the mean.

6.3.3 Discussion

By forcing participants to explore visual stimuli serially using aperture viewing we slowed down stimulus presentation so information was acquired more serially and was analysed locally and so visual perception became more like haptic perception. The results for visual repetition detection using aperture viewing revealed no two-objects advantage, similar to the result that we have previously obtained for haptic repetition detection for vertically aligned stimuli (left column of Figure 6, Experiment 1 of Cecchetto & Lawson, in press; see also Lawson et al., in press). Visual symmetry detection was faster

and more accurate for one-object stimuli than for two-objects stimuli, replicating the one-object advantage for both visual and haptic symmetry detection reported by Cecchetto and Lawson (in press). Thus the regularity-type by objectness interaction obtained for visual regularity detection by Cecchetto and Lawson (in press) was weaker due to the lack of a two-objects advantage for repetition detection. Finally, there was no overall symmetry advantage relative to repetition which contrasts to the usual finding for both vision and touch (see Cecchetto & Lawson, in press). These results differ from the results which we previously obtained for visual regularity detection using normal, simultaneous stimulus presentation (right column of Figure 6, Cecchetto & Lawson, in press), supporting the idea that regularity detection depends on how information is acquired. However, the results also differed from those obtained for haptic regularity detection.

For symmetrical stimuli, equivalent points along pairs of critical contours on either side of an object have matching polarities of concavities and convexities, whereas contour polarity mismatches for repetition stimuli. Baylis and Driver (1995) argued that the symmetry advantage for one-object stimuli may arise because contour polarities matched and, hence, the segmentation of the object into parts matched, based on Hoffman and Richards' (1984) theory of parts decomposition. Hoffman and Richards suggested that the shape of an object can be represented in terms of the layout of its convex parts, with adjacent parts being separated by points of concavity, which they referred to as negative minima of curvature (for more recent research in this topic, see for example Leek, Cristino, Conlan, Patterson, Rodriguez & Johnston, 2012; Lim & Lee, 2012). In contrast, the detection of repetition for one-object stimuli might require a less efficient, serial processing of vertices, since both contour polarities and parts decomposition mismatch (for a recent review on contour polarity, see Bertamini & Wagemans, 2013). By forcing exploration to be serial in Experiment 1, we may have ensured that part decomposition was serial for symmetry as well as for repetition, making regularity detection for symmetry more like that of repetition. In Experiment 1, we contrasted our results to those obtained in previous visual and haptic regularity detection studies (Cecchetto & Lawson, in preparation). However, these previous studies used different participants and there were some differences in the stimuli (for example, whether vertices were angular or rounded) and the tasks used. In Experiment

2 we used a within-participants design in order to try to replicate and extend the results of Experiment 1.

6.4 Experiment 2

We had two aims in Experiment 2. First, we directly compared serial exploration of stimuli using an aperture to simultaneous presentation of the same stimuli using the same regularity detection task and the same participants. Unlike the unlimited duration simultaneous presentation condition used by Cecchetto and Lawson (in preparation), in Experiment 2 the whole stimulus was shown simultaneously for only a brief time in order to approximately equate difficulty with the serial exploration condition.

Second, we investigated how contour complexity affected regularity detection by presenting simple stimuli with four vertices (as in Experiment 1) and complex stimuli with nine vertices. In a series of studies, Baylis and Driver (1994, 2001) manipulated shape complexity by varying the number of discontinuities along pairs of critical contours of novel 2D shapes. They found that repetition detection was always much harder for more complex stimuli whereas there was little disadvantage for increasing complexity for symmetry detection for one-object stimuli. For example, Baylis and Driver (2001) reported a cost of around 5ms/discontinuity for symmetrical, one-object stimuli, compared to 31ms/discontinuity for repetition, one-object stimuli. However, they found that symmetry detection also showed a substantial disadvantage with increased complexity for two-objects objects even if contour polarities and parts decomposition of both objects matched. They therefore concluded that complexity could only be dealt with efficiently when both pairs of critical contours led to the same parts decomposition for a single shape. In all other situations, Baylis and Driver argued that increasing complexity directly increased task difficulty because regularities had to be dealt with using an effortful and time-consuming, point-by-point, serial matching strategy. The claim that symmetry detection relies on simultaneous processing of the whole stimulus whereas repetition detection relies on serial processing has been widely accepted but most of the evidence for it comes

from visual search studies (Huang, Pashler & Junge, 2004; Olivers & van der Helm, 1998; van der Helm & Leeuwenberg, 1996).

Baylis and Driver (1994, 2001) presented each stimulus until the participant responded and they only manipulated regularity-type and complexity. In Experiment 2, we presented one-object stimuli only and we manipulated the nature of visual exploration as well as regularity-type and complexity. We compared regularity detection for simultaneous presentation versus serial exploration using the same aperture condition tested in Experiment 1. Based on the one-object results of Baylis and Driver (1994, 2001), for simultaneous presentation we expected that increasing stimulus complexity would make repetition detection harder but would not affect symmetry detection. In contrast, based on the one-object results of Experiment 1, for serial exploration we predicted that people would perform similarly for symmetry detection and repetition detection and we also predicted that both symmetry and repetition detection would be harder for more complex stimuli because aperture viewing would force processing to proceed serially.

6.4.1 Method

6.4.1.1 Participants

A further 24 students from the University of Liverpool (13 females, mean age = 23.6 years, s.d. = 4.6, range 18-32) took part in Experiment 2, with most receiving course credit. All participants declared having normal or corrected-to-normal vision and self-reported as right handed.

6.4.1.2 Materials

A set of 320 stimuli was used. These comprised the 160 one-object stimuli used in Experiment 1 (the simple stimuli, with four vertices) and 160 new stimuli (the complex stimuli, with nine vertices). Complex stimuli were created using Inkscape by duplicating each of the simple stimuli and then placing one on top of the other, see Figure 7. The vertex connecting the two copies was smoothed and rounded. This duplicated stimulus was then

squashed by halving its height (from 20cm to 10cm) so that the height and width of each complex stimulus matched that of the simple stimuli.

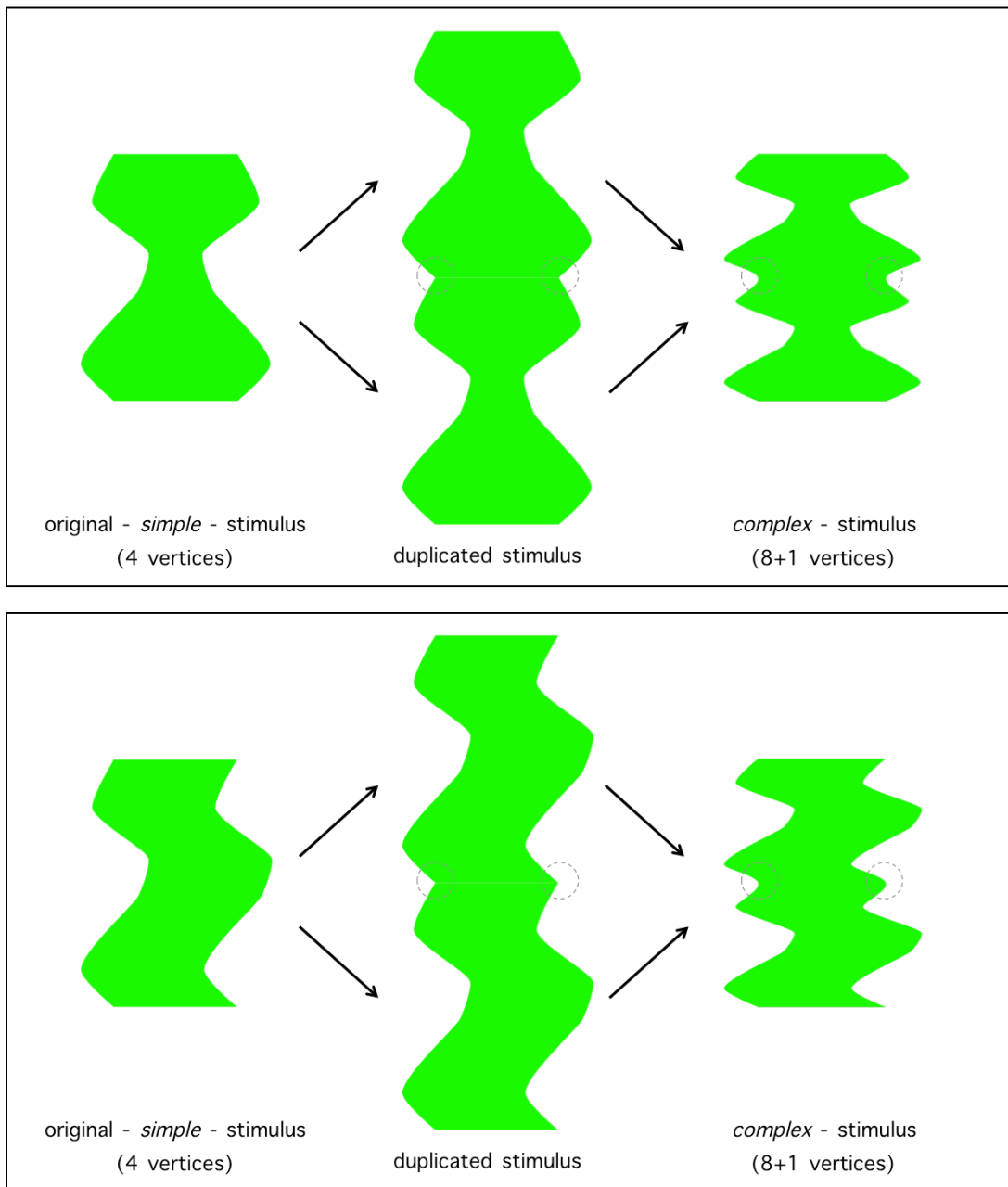


Figure 7. Creation of the symmetrical (top) and repetition (bottom) complex stimuli for Experiment 2 from the original, one-object simple stimuli used in Experiment 1. The dashed circles indicate where the join between the two halves of the duplicated stimulus were smoothly interpolated to create a ninth, rounded vertex in the complex stimulus.

6.4.1.3 *Design and Procedure*

The 320 stimuli were divided into two subsets of 160. The two sets were approximately matched in terms of difficulty, on the basis of the accuracy in detection that we observed in our previous haptic experiment (see Cecchetto & Lawson, in press) by ordering each unique line's performance for regularity detection, from best to worst and then placing alternate lines into each subset. In the serial exploration condition, responses were expected to be much slower than in the simultaneous presentation condition so only one subset was presented to a given participant, with half of the stimuli presented in a block of 80 symmetry detection trials and the remaining trials presented in a block of 80 repetition detection trials. For the simultaneous presentation condition, all 320 stimuli were presented to every participant, in a block of 160 symmetry detection trials and a block of 160 repetition detection trials. For both conditions, block order (symmetry first or repetition first) was counterbalanced across participants and trial presentation order was randomized within each block for each participant. Within each block the first half of trials used serial exploration and the second half used simultaneous presentation for half the participants and the reverse order for the other participants, with the same type of stimulus presentation used in the first and third sub-blocks and in the second and fourth sub-blocks. Equal numbers of participants were allocated to each counterbalancing condition.

For serial exploration the procedure was similar to Experiment 1 except that the stimuli were not presented stereoscopically and so no 3D glasses were used. For simultaneous presentation, a white fixation cross appeared on a black background for 0.5s. This was replaced by the stimulus which was identical to the serial exploration stimulus except that there was no black mask containing an aperture, see Figure 8. The stimulus was displayed for 0.5s¹ and it was then replaced by visual noise until the participant responded. The stimulus duration was chosen to avoid ceiling and floor effects for symmetry and repetition detection and to approximately match performance across the serial exploration and simultaneous presentation conditions. Participants sat directly in front of the monitor. The keyboard was moved from their left side, where it was placed during serial exploration, and was placed in front of them, see Figure 8. Participants pressed 'h' or 'k' for regular and irregular stimuli

respectively, using their left and right index fingers respectively. The experiment lasted about 45 minutes.

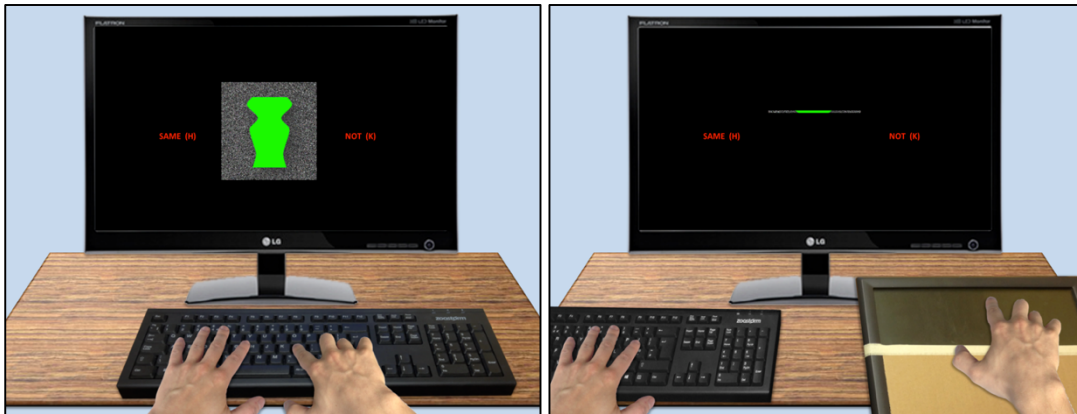


Figure 8. An illustration of the two visual exploration conditions tested in Experiment 2, shown from the participant's point. On the left, simultaneous presentation: on the right, serial exploration.

6.4.2 Results

Two participants were replaced because they performed poorly, making over 25% errors. For serial exploration trials, correct RT faster than 0.5s and slower than 20s were removed as outliers (less than 1% of trials). For simultaneous presentation trials, correct RT faster than 0.5s or slower than 2.5s were removed as outliers (less than 1% of trials). As in Experiment 1, ANOVAs were conducted on the mean correct RT and on the percentage of errors for regular trials only. There were three within-participants factors: regularity-type (symmetry or repetition), complexity (simple or complex) and presentation (simultaneous or serial). Unlike Experiment 1, there was no objectness factor because all the stimuli in Experiment 2 were one-object stimuli. All pairwise differences noted below were significant ($p < .05$) in post-hoc Newman-Keuls analyses.

For RT, the only significant effects were for presentation [$F(1,23) = 82.17$, $p < .001$, partial $\eta^2 = .78$] and regularity-type [$F(1,23) = 7.49$, $p = .012$, partial $\eta^2 = .25$]; complexity and all the interactions involving complexity were not significant ($p > .05$). RT were faster for simultaneous presentation (0.93s) than for serial exploration (3.62s) and they were faster for symmetry detection (2.07s) than for repetition detection (2.48s).

For errors, all the main effects and interactions were significant ($p < .01$) including the three-way interaction [$F(1,23) = 6.66, p = .017, \text{partial } \eta^2 = .22$]. To breakdown this interaction and to simplify the presentation of the results, we analysed the results for the two exploration conditions separately (see Figure 9).

Brief simultaneous presentation

Regularity-type was significant for both RT $F(1,23) = 40.56, p < .001, \text{partial } \eta^2 = .64$] and errors [$F(1,23) = 97.23, p < .001, \text{partial } \eta^2 = .81$]. Symmetry (0.79s, 4.2% errors) was detected faster and more accurately than repetition (1.07s, 20.8%). Complexity was also significant for both RT [$F(1,23) = 41.73, p < .001, \text{partial } \eta^2 = .65$] and errors [$F(1,23) = 12.13, p = .002, \text{partial } \eta^2 = .35$]. Simple stimuli (0.91s, 9.1%) were detected faster and more accurately than complex stimuli (0.96s, 16%). Finally the interaction of regularity-type \times complexity was significant for both RT [$F(1,23) = 12.88, p = .002, \text{partial } \eta^2 = .36$] and errors [$F(1,23) = 9.60, p = .005, \text{partial } \eta^2 = .30$]. For symmetry, there was no difference between detecting simple (0.79s, 3.6%) and complex (0.80s, 4.8%) stimuli. However, for repetition, simple stimuli (1.02s, 14.5%) were detected faster and more accurately than complex stimuli (1.11s, 27.2%). This pattern of results replicated that obtained by Baylis and Driver (2001) for simultaneously presented, one-object stimuli, namely a complexity cost for repetition but not for symmetry detection.

Serial (aperture) exploration

There were no significant effects. Regularity-type was not significant for either RT [$F(1,23) = 3.69, p = .067, \text{partial } \eta^2 = .14$] or errors [$F(1,23) = .27, p = .607, \text{partial } \eta^2 = .01$], though there was a trend for symmetry (3.33s, 6.9%) to be detected faster than repetition (3.90s, 6%). There was no effect of complexity for RT [$F(1,23) = .11, p = .745, \text{partial } \eta^2 = .01$] or errors [$F(1,23) = .24, p = .627, \text{partial } \eta^2 = .01$]. Detection was similar for simple (3.60s, 6.1%) and complex (3.63s, 6.8%) stimuli. Finally, the interaction of regularity-type \times complexity was not significant for either RT [$F(1,23) = .81, p = .378, \text{partial } \eta^2 = .03$] or errors [$F(1,23) = .78, p = .385, \text{partial } \eta^2 = .03$]. Detection was similar for simple, symmetrical (3.27s, 5.8%), complex symmetrical (3.40s, 7.9%), simple

repetition (3.93s, 6.5%) and complex repetition (3.87s, 5.6%) stimuli. This pattern of results thus differed substantially to that for simultaneous presentation.

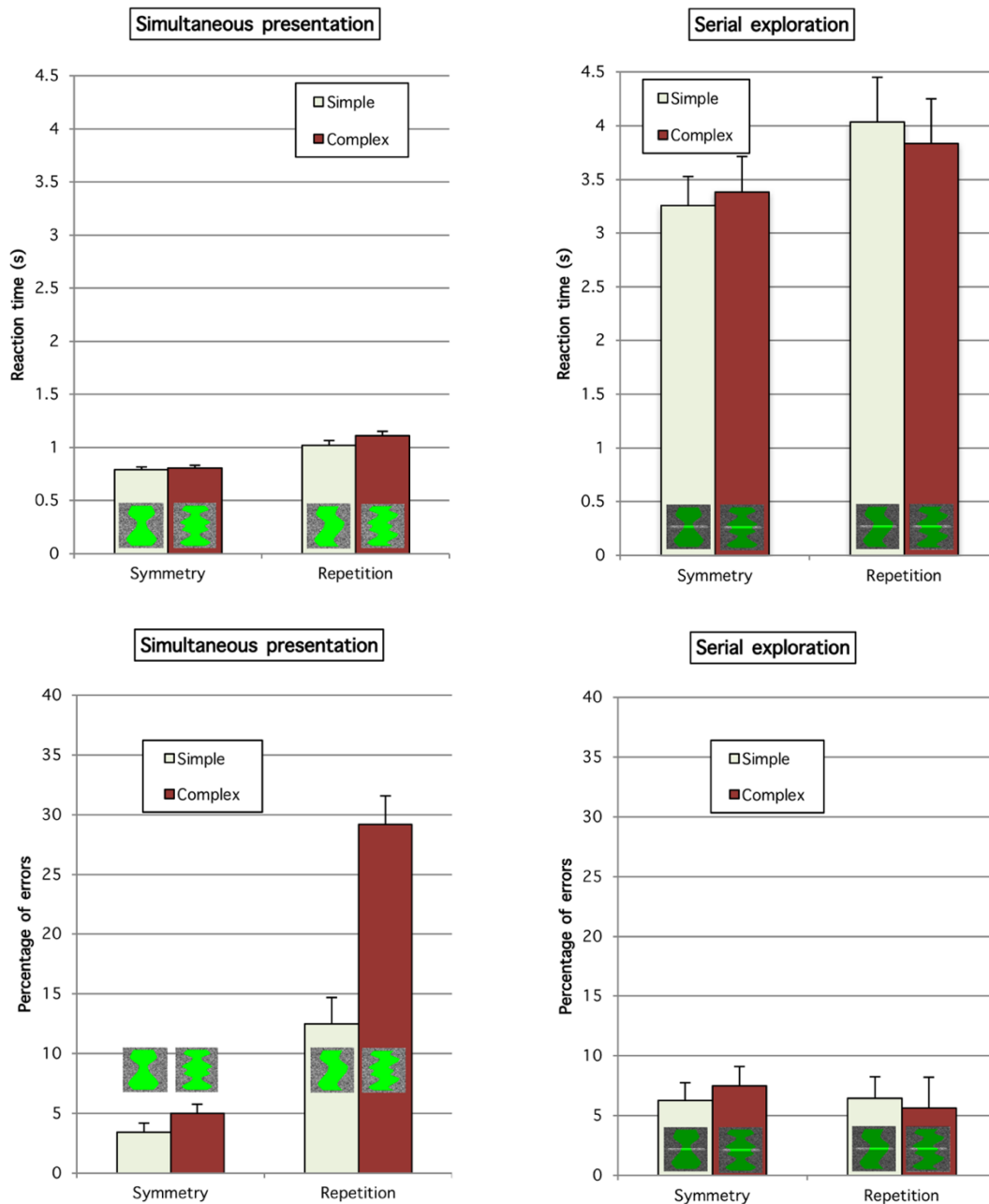


Figure 9. Results for regular trials for Experiment 2, for the visual detection of symmetry and repetition for simultaneous presentation (left) and for serial exploration (right), for RT (top) and for errors (bottom). Error bars represent one standard error of the mean.

6.4.3 Discussion

Experiment 2 once again revealed a critical role of exploration in the visual detection of regularities. The results for the simultaneous presentation replicated the overall pattern of results reported by Baylis and Driver (1994; 2001) for one-object stimuli. Symmetry was easier to detect than repetition and was immune to changes in complexity whereas repetition was harder to detect for more complex stimuli. These results are consistent with Baylis and Driver's account which suggests that part decomposition can proceed simultaneously across the whole stimulus for symmetrical, one-object stimuli only because, here, the contour polarities of the two critical contours are matched. This means that the object parts can be extracted efficiently at concavities, as originally proposed by Hoffman and Richards (1984).

In contrast, for serial exploration, replicating Experiment 1, the usual advantage of symmetry over repetition was lost. Furthermore, there were no effects of complexity. In contrast to the results for simultaneous presentation, here symmetry detection behaved more like repetition detection. However, we should note that analysis of the irregular trials revealed a symmetry advantage compared to repetition. In Experiment 2 participants may have adopted different strategies during detection of the two types of regularities. We have no theoretical account of why this finding occurred.

6.5 Experiment 3

In Experiment 2 stimuli were presented only briefly in the simultaneous presentation condition in order to make the task harder to try to make it more similar to the serial exploration condition. However, this meant that the stimulus presentation differed from the unlimited presentation durations used in our previous studies (Cecchetto & Lawson, in press; Cecchetto & Lawson, in preparation; Lawson et al., in press). The final experiment investigated whether presentation duration had different effects on symmetry detection compared to repetition detection for simultaneously presented stimuli. In Experiment 3 stimuli were presented for either a limited duration (0.5s, as in Experiment 2) or an unlimited duration (the stimulus remained on the screen until the participant responded, as in our previous studies). We did

this in order to test whether the complexity effects observed in Experiment 2 were reduced or eliminated if participants had sufficient time to encode the entire stimulus. This prediction was made because for unlimited stimulus presentation there should be a reduced cost - at least for accuracy - for serial processing.

6.5.1 Method

6.5.1.1 Participants

A further 24 students from the University of Liverpool (1 male, mean age = 19.9 years, s.d. = 5.8, range 18-47) took part in Experiment 3, with most receiving course credit. All participants declared having normal or corrected-to-normal vision and self-reported as right handed.

6.5.1.2 Materials

These were the same as in Experiment 2 except that the whole set of 320 stimuli was presented to each participant for both regularities, giving a total of 640 trials.

6.5.1.3 Design and Procedure

The design was identical to Experiment 2, except that the serial exploration condition was replaced by a second simultaneous presentation condition with an unlimited presentation duration. The counterbalancing was identical to Experiment 2 except that the factor of presentation (simultaneous or serial) was replaced by the factor of duration (brief or unlimited) and there were four blocks of 160 trials for each participant. The procedure for the brief duration condition was identical to that for the simultaneous presentation condition tested Experiment 2, with stimuli presented for 0.5s before being replaced by background noise. The same procedure was used for the unlimited duration condition except that the stimulus remained visible until the participant responded. The experiment took about 40 minutes.

6.5.2 Results

Two participants were replaced because they performed poorly, making over 25% errors. Correct RT faster than 0.4s or slower than 5s were removed as outliers (less than 1% of trials). As in Experiments 1 and 2, ANOVAs were conducted on the mean correct RT and on the percentage of errors for regular trials only. There were three within-participants factors: regularity-type (symmetry or repetition), complexity (simple or complex) and duration (brief or unlimited). As in Experiment 2, but unlike Experiment 1, there was no objectness factor because all the stimuli in Experiment 3 were one-object stimuli. All pairwise differences noted below were significant ($p < .05$) in post-hoc Newman-Keuls analyses.

Regularity-type was significant for both RT [$F(1,23) = 80.23, p < .001$, partial $\eta^2 = .77$] and errors [$F(1,23) = 67.69, p < .001$, partial $\eta^2 = .75$]. Symmetry (0.66s, 5.7%) was detected faster and more accurately than repetition (1.15s, 19.3%). Complexity was significant for both RT [$F(1,23) = 67.95, p < .001$, partial $\eta^2 = .75$] and errors [$F(1,23) = 111.22, p < .001$, partial $\eta^2 = .83$]. Simple stimuli (0.83s, 7.5%) were detected faster and more accurately than complex ones (0.98s, 17.6%). Duration was significant for both RT [$F(1,23) = 28.26, p < .001$, partial $\eta^2 = .55$] and for errors [$F(1,23) = 36.35, p < .001$, partial $\eta^2 = .61$]. RT were slower but accuracy was greater for unlimited (1.03s, 10.0% errors) than brief (0.77s, 15.2%) duration trials so there was a speed-accuracy trade-off here which was not surprising given the experimental manipulation.

The interaction of duration x regularity-type was significant for both RT [$F(1,23) = 18.98, p < .001$, partial $\eta^2 = .45$] and errors [$F(1,23) = 4.51, p = .045$, partial $\eta^2 = .16$]. For unlimited durations, symmetry (0.69s, 4.1%) was detected faster and more accurately than repetition (1.38s, 15.7%). For brief durations, symmetry (0.62s, 7.3%) was also easier to detect than repetition (0.93s, 23.0%). The interaction of duration x complexity was significant for RT [$F(1,23) = 25.09, p < .001$, partial $\eta^2 = .52$] but it was not for errors [$F(1,23) = .032, p = .860$, partial $\eta^2 = .00$]. For brief durations, simple stimuli were detected faster (simple: 0.74s, 10.1%; complex: 0.81s, 20.3%), and the same occurred for unlimited durations (simple: 0.92s, 4.9%; complex: 1.15s, 14.8%). The interaction of regularity-type x complexity was significant for both RT [$F(1,23) = 29.47, p < .001$, partial $\eta^2 = .56$] and errors [$F(1,23) = 30.53, p < .001$, partial $\eta^2 = .57$]. For symmetry detection there was no difference between simple (0.62s, 3.8%) and complex

(0.68s, 7.6%) stimuli; however, for repetition detection simple stimuli (1.03s, 11.2%) were detected faster and more accurately than complex ones (1.28s, 27.5%). The three way interaction of regularity-type x complexity x duration was significant for RT [$F(1,23) = 16.27, p = .001, \text{partial } \eta^2 = .41$] but not for errors [$F(1,23) = 3.78, p = .064, \text{partial } \eta^2 = .14$]. To breakdown this interaction, and to simplify the presentation of the results, we analysed the results for the two duration conditions separately (see Figure 10).

Brief simultaneous presentation

Regularity-type was significant for both RT [$F(1,23) = 176.95, p < .001, \text{partial } \eta^2 = .89$] and errors [$F(1,23) = 47.91, p < .001, \text{partial } \eta^2 = .68$]. Symmetry (0.62s, 7.3%) was detected faster and more accurately than repetition (0.93s, 23%). Complexity was also significant for both RT [$F(1,23) = 32.84, p < .001, \text{partial } \eta^2 = .59$] and errors [$F(1,23) = 65.12, p < .001, \text{partial } \eta^2 = .74$]. Simple stimuli (0.74s, 10.1%) were detected faster and more accurately than complex stimuli (0.81s, 20.3%). Finally, the interaction of regularity-type x complexity was significant for both RT [$F(1,23) = 6.83, p = .016, \text{partial } \eta^2 = .23$] and errors [$F(1,23) = 15.29, p < .001, \text{partial } \eta^2 = .40$]. For symmetry, simple stimuli (0.60s, 4.8%) were easier to detect than complex stimuli (0.64s, 9.9%). Likewise, for repetition, simple stimuli (0.88s, 15.3%) were easier to detect than complex stimuli (0.98s, 30.6%). Repetition had a greater absolute cost (though a similar proportional cost) of increasing complexity relative to symmetry detection.

Unlimited simultaneous presentation

Regularity-type was significant for both RT [$F(1,23) = 50.41, p < .001, \text{partial } \eta^2 = .69$] and errors [$F(1,23) = 63.49, p < .001, \text{partial } \eta^2 = .73$]. Symmetry (0.69s, 4.1%) was detected much faster and more accurately than repetition (1.38s, 15.7%). Complexity was also significant for both RT [$F(1,23) = 52.05, p < .001, \text{partial } \eta^2 = .69$] and errors [$F(1,23) = 56.18, p < .001, \text{partial } \eta^2 = .71$]. Simple stimuli (0.92s, 4.9%) were detected faster and more accurately than complex stimuli (1.15s, 14.8%). Finally, the interaction of regularity-type x complexity was significant for both RT [$F(1,23) = 26.33, p < .001, \text{partial } \eta^2 = .53$] and errors [$F(1,23) = 35.27, p < .001, \text{partial } \eta^2 = .61$]. For symmetry, there

was no difference between detecting simple (0.66s, 2.8%) and complex (0.73, 5.3%) stimuli. However, for repetition, simple stimuli (1.18s, 7.1%) were detected faster and more accurately than complex stimuli (1.56s, 24.4%).

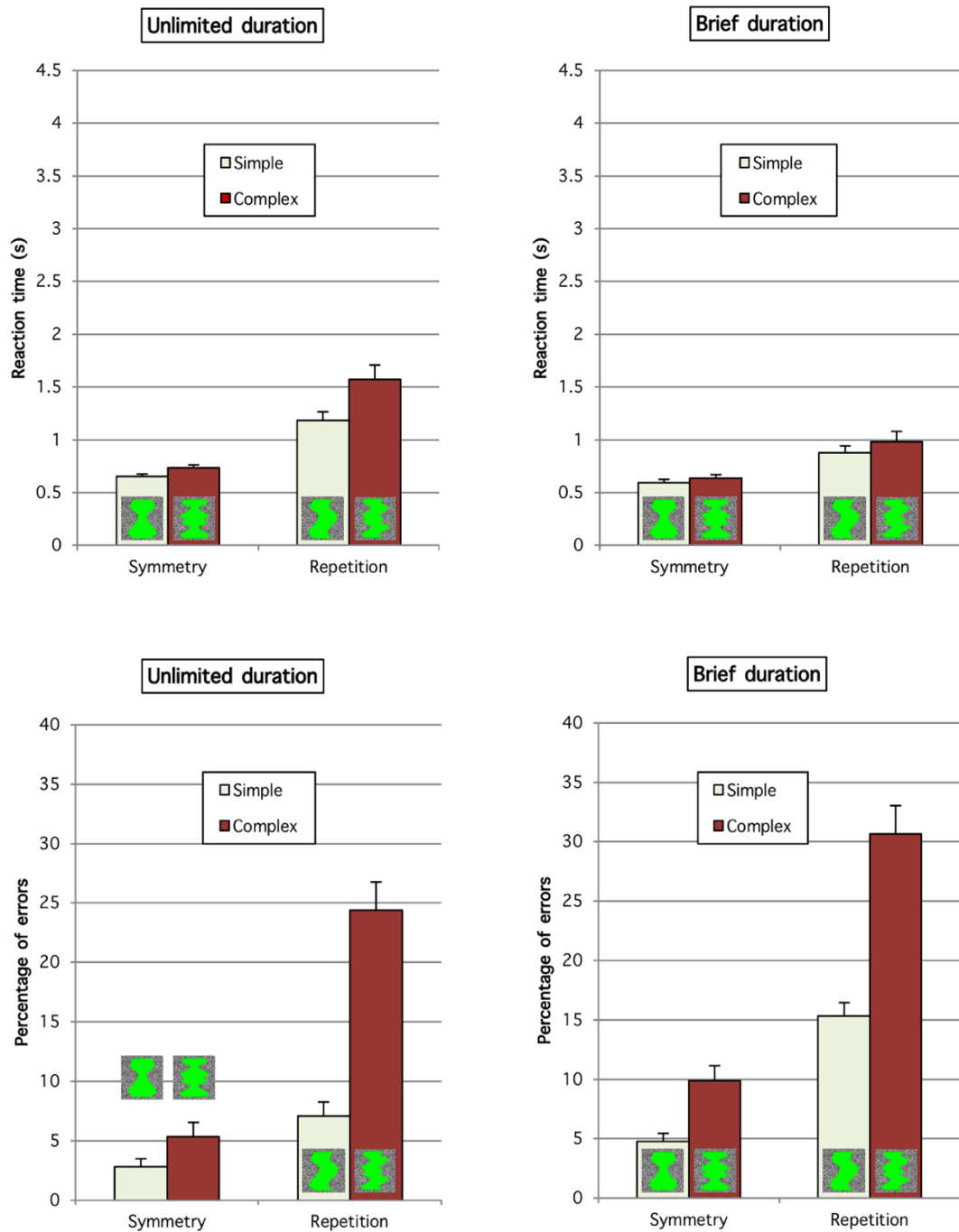


Figure 10. Results for regular trials for Experiment 3, for the visual detection of symmetry and repetition, for simultaneous presentation of unlimited duration (left) and of brief duration (right), for RT (top) and for errors (bottom). The brief duration condition replicated the simultaneous presentation condition in Experiment 2 (shown in the left column of Figure 9). Error bars represent one standard error of the mean.

6.5.3 Discussion

The results of Experiment 3 for stimuli presented simultaneously for an unlimited duration were similar to those of Baylis and Driver (2001) and of Experiment 2 for the simultaneous presentation condition. Repetition detection was always disrupted by increased complexity, whereas symmetry detection was less sensitive to complexity. Symmetry detection showed no significant cost of increasing complexity for stimuli presented for an unlimited duration and it showed a reduced cost compared to repetition detection for stimuli presented briefly. However, the latter effect of complexity on symmetry detection in the brief duration condition contrasted to the lack of a significant effect of complexity on symmetry detection in Experiment 2 and in the results of Baylis and Driver (1994, 2001). Nevertheless, a trend was found for a cost of increasing complexity for symmetry detection for the unlimited duration condition in Experiment 3 here, as well as for the simultaneous presentation condition in Experiment 2, and in Baylis and Driver (1994, 2001). Therefore a better summary of all of the results obtained to date is not that complexity has no influence on symmetry detection, but rather that the cost of increasing complexity on regularity detection is greater for repetition than for symmetry, except when stimuli are explored serially, as in Experiment 2.

6.6 General Discussion

In three experiments, we provided evidence that the manner of stimulus exploration plays a crucial role in visual regularity detection. These results suggest that effects on regularity detection are informative about the manner in which stimuli are processed rather than only reflecting intrinsic, physical properties of our environment. In our previous research, we found differences in regularity detection between vision and haptics (Cecchetto & Lawson, in preparation; Cecchetto & Lawson, in press; Lawson et al., in press). In particular, for visual regularity detection we found an interaction between regularity-type and objectness with a two-objects advantage for repetition detection but not symmetry detection (Cecchetto & Lawson, in press; see also Koning & Wagemans, 2009). In contrast, for haptics we found a one-object

advantage for both symmetry and repetition. In the present study, we hypothesized that one reason for this modality-specific difference could be the different ways in which vision and haptics explore and acquire information from the world. Vision can often rely on fast processing of the whole stimulus simultaneously, whereas haptics typically requires slower, serial exploration of a succession of small areas of the stimulus. Here, we investigated what would happen if vision was forced to perceive the world more like haptics.

In Experiment 1, we forced vision to explore stimuli serially using a movable aperture to restrict the field of view so that only a small area of the stimulus could be seen at a given time (see also Craddock et al., 2011; Loomis et al., 1991; Martinovic et al., 2012). We then re-examined the effect of manipulating objectness on symmetry compared to repetition detection. Encoding spatial information serially due to an extended period of exploration is a less efficient way to build up a unitary spatial representation (Ruggiero & Iachini, 2010; Vecchi, Tinti & Cornoldi, 2004). Serialising visual presentation by using an aperture eliminated the two-objects advantage for repetition detection and so, consistent with our predictions, it made visual regularity detection more like that of haptics (Cecchetto & Lawson, in press). However, there was still a regularity-type by objectness interaction with a greater one-object advantage for symmetry detection compared to repetition detection whereas this interaction was eliminated for haptics (Cecchetto & Lawson, in press). In addition, there was no overall advantage for symmetry detection compared to repetition detection, contrary to the results for both visual and haptic regularity detection which we reported previously (Cecchetto & Lawson, in press). This suggests that serialising visual exploration only partially mimics haptic exploration or that different processes are involved in visual and haptic regularity detection.

In Experiment 2 we built upon the results from Experiment 1. First, we extended Experiment 1 by directly comparing regularity detection for serial exploration (using aperture viewing) versus normal, simultaneous presentation of the stimulus for one-object stimuli. In addition, we presented stimuli varying in complexity in order to explore an interaction between regularity-type and complexity that was originally reported by Baylis and Driver (1994, 2001). Baylis and Driver found that increasing complexity by increasing the number of discontinuities in the critical contours of one-object

stimuli had no effect on symmetry detection but that it made repetition detection slower and less accurate. Baylis and Driver (1994, 2001) explained these results by suggesting that symmetry could be detected in simultaneously for the whole stimulus, whereas for repetition each vertex needed to be analysed serially, so each extra vertex slowed performance. Based on Hoffman and Richards' (1984) theory of object perception, they noted that objects with symmetrical pairs of critical contours had matching contour polarities and that this led to efficient decomposition of the stimulus into parts using the minima rule whereas objects with repeated pairs of contours did not have matching parts decomposition, resulting in more effortful object perception.

In Experiment 2 we provided empirical evidence for the claims of Baylis and Driver (1994, 2001) since we found no cost of increasing complexity for symmetry detection whereas repetition detection for complex stimuli was substantially harder than for simple stimuli. In contrast, for serial exploration we found no effects of complexity. Here, we suggest that participants could just vary the speed at which they moved the aperture when they were comparing the two critical contours on each side of the object. If they moved the aperture around twice as fast for the simple stimuli they could make the same number of pairwise comparisons and they would acquire similar amounts of evidence for the presence of regularity before they responded. This account is consistent with RT being similar across the simple and complex conditions for both symmetry and repetition in the serial exploration condition (see the right side of Figure 9). Object perception for stimuli explored serially, using aperture viewing, is known to depend on several factors including the speed with which the aperture is moved and properties of the object (e.g., Anstis & Atkinson, 1967; Haber & Nathanson, 1968). Future research should experimentally manipulate the speed with which the aperture can be moved to examine whether the rate of information acquisition influences complexity effects.

In the simultaneous presentation condition for Experiment 2, each stimulus was presented for 0.5s, and then was replaced by noise, encouraging simultaneous processing of the whole stimulus at once. In contrast, in the studies reported by Baylis and Driver (1994, 2001) stimuli were presented until the participant responded. In Experiment 3, we directly investigated whether

the duration of stimulus presentation influenced regularity detection. Regardless of presentation duration, repetition detection was always disrupted by increased complexity. In contrast, symmetry detection showed no significant cost of increasing complexity for unlimited duration presentations, and a weaker cost of complexity compared to repetition detection for stimuli presented briefly. Considering the results of Experiments 2 and 3 together with those of Baylis and Driver (1994, 2001) we conclude that there is a greater cost of increasing complexity on repetition detection than symmetry detection when stimuli are presented simultaneously. The cost of increased complexity for repetition detection is usually large and statistically significant whereas the cost of increased complexity for symmetry detection is usually small and is often not significant. In contrast, when stimuli are explored serially, using aperture viewing, complexity has no influence on regularity detection for either symmetry detection or repetition detection.

Our attempt to reduce the differences between visual and haptic perception by using aperture viewing could be critiqued. For instance, vision and haptics may adopt completely different strategies to achieve regularity detection. For example, haptics - but not vision - could rely on proprioception, with symmetry detected when hand and arm movements are symmetrical, or when the fingers approach the midline together, whilst repetition could be detected when the perceived distance between the two exploring fingers remains constant and the two hands and arms make parallel, repeated movements during contour exploration. These latter possibilities could be tested directly by forcing participants to use different exploratory movements (such as asynchronous movements or movements that are not aligned symmetrically with the body midline) during haptic regularity detection in order to test whether this influenced performance.

In conclusion, the results of this study, together with those of our previous experiments (Cecchetto & Lawson, in preparation; Cecchetto & Lawson, in press; Lawson et al., in press), support the claim that modality-specific effects play a dominant role in determining how regularities are detected. Making visual exploration slow and serial made visual regularity detection more like haptic regularity detection and less like visual regularity detection with simultaneous presentation in terms of the effects of objectness and stimulus complexity. These results indicate the crucial importance of the

manner of exploration in determining how shapes are represented and what aspects of the stimulus are salient to perception.

Footnotes

1 Due to a coding error in the simultaneous presentation condition in Experiment 2, RT were recorded from the stimulus offset until the participant's response. RT to any response that occurred before the offset of the stimulus was recorded as 0s (4.2% of trials). We added 0.5s to every RT. This meant that RT occurring after the stimulus offset were correct but any faster RT were rounded up to 0.5s. RT were recorded correctly in Experiment 3 and the results here were similar to those of Experiment 2 for the unlimited presentation condition which matched the simultaneous presentation condition tested in Experiment 2.

Part 3

Symmetry detection and preference
judgment using 3D novel objects

Chapter 7

7 Investigating the role of spatial frames of reference in a symmetry detection task using 3D novel objects.

* This study is in preparation for submission as: Cecchetto, S & Lawson, R. Investigating the role of spatial reference in a symmetry detection task using 3D novel objects. (In preparation)

7.1 Abstract

Symmetry is a spatial property possessed by many objects in both the natural and artificial world. We are very sensitive to visual symmetry, and we are also able to detect symmetry by haptics, our sense of active touch. Previous studies confirmed a bimanual advantage when trying to detect symmetry for objects with the axis of symmetry aligned with the body of the observer. This may be because this alignment facilitates the use of the body as a perceptual reference frame. However, this advantage might also depend on the position of the hands around the object (hand-centred reference frame). In this study, we tested which of these reference frames was associated with an advantage for haptic symmetry detection. We manipulated orientation of the axis of symmetry (aligned or across the body midline) and object position (front or right side) relative to the participant's body. We hypothesized that differences in bimanual symmetry detection position would support the use of a body-centred reference frame whereas a lack of effect of orientation would support the use of a hand-centred reference frame. We found evidence for both predictions because both the position of the object relative to the body and the

orientation of the object's axis of symmetry relative to the hands influenced performance. Symmetry was detected more accurately when aligned-axis objects were positioned in front of the participant relative to the other three conditions, which did not differ from each other. However, both effects were modest demonstrating the flexibility and robustness of haptic processing.

7.2 Introduction

We do not need to look hard in the environment to realise how many symmetrical shapes surround us. Many of the natural and artificial objects we interact with are more or less symmetrical. Indeed, our own bodies, including our faces, are symmetrical. The frequency with which we encounter symmetry in the world is possibly the reason we are so good at detecting this regularity in the world, not only by vision, but also by haptics, our sense of active touch (for vision reviews, see Giannouli, 2013; Treder, 2010; Tyler, 1995; van der Helm, 2014; Wagemans, 1997; for a recent haptic review, see Cattaneo, Bona, Bauer, Silvanto, Herbert, Vecchi & Merabet, 2014).

In everyday language, symmetry usually refers to bilateral mirror symmetry. However, in more formal language, the term symmetry also encompasses other spatial regularities such as the repetition of a structure by a translation (translational symmetry) and the rotation of a structure around 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 are concerned only with bilateral, mirror-reflective symmetry (henceforth termed *symmetry*), which is usually easier to detect than either translational or rotational symmetries (Julesz, 1971).

Considerable effort has been devoted to explaining how and why visual symmetry can be detected so efficiently (Wagemans, 1995; 1997) and why we are so attracted to it (Ramachandran & Hirstein, 1999). Symmetry is known to be one of the major grouping principles for the representation of visual shapes (e.g., 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). Symmetry has been shown to be a crucial factor in the recognition processes of both 2D shapes (e.g., Giaquinto, 2005; Marr & Nishihara, 1978) and 3D objects (Large, McMullen & Hamm, 2003; Liu & Kersten, 2003; Sekuler & Swimmer, 2000; Vetter & Poggio, 1994). Symmetry about a vertical axis is usually the easiest to recognize for humans (e.g., Machilsen et al., 2009; Wenderoth, 1994).

However, vision is not the only sensory modality that allows us to explore and perceive objects in the world. Many objects can also be efficiently recognised by haptics. The haptic perceptual system encodes information from cutaneous and kinaesthetic receptors (Loomis & Lederman, 1986) and, like vision, it can be accurate at identifying familiar objects (Klatzky, Lederman & Metzger, 1985; Lawson & Bracken, 2011) and at detecting attributes of the spatial layout of tangible displays such as object shape, size and orientation (Lawson, 2009; Kappers & Bergmann Tiest, 2013) including bilateral symmetry (e.g., Ballesteros, Manga & Reales, 1997; Ballesteros, Millar & Reales, 1998; Ballesteros & Reales, 2004).

The present study investigated the role of object orientation relative to the participant in haptic perception of symmetry. Provided that an object is sufficiently small, our hands can usually explore it fully. Nevertheless, previous research on haptic object recognition has found orientation effects (Craddock & Lawson, 2008; Ernst, Lange, & Newell, 2007; Lawson, 2009, 2011). This suggests that, during haptic exploration, shape representation is not coded in an object-centred reference frame since the orientation of the object relative to the body of the observer influences performance.

Millar (1994) proposed the reference hypothesis which suggests that accurate haptic shape recognition and spatial perception depends on using information about spatial frames of reference to aid stimulus coding. As a consequence, symmetry detection depends on the availability of spatial reference information. According to this, haptic symmetry perception is more sensitive to stimulus orientation than that of vision because of the relative lack of spatial reference cues (Millar, 1994). Consistent with this, sensitivity to orientation has been found in previous haptic symmetry detection tasks using 2D stimuli (e.g., Ballesteros et al., 1998; Cecchetto & Lawson, in press) raised lines (Lawson, Ajvani & Cecchetto, in press), and in memory tasks

investigating the effects of symmetry (Cattaneo, Fantino, Silvano, Tinti, Pascual-Leone & Vecchi, 2010; Cattaneo, Vecchi, Fantino, Herbert & Merabet, 2013). For example, the use of the body midline in spatial tasks (body-centred reference frame) improved spatial performance in many haptic studies. We now focus on those studies conducted by Ballesteros and colleagues.

Ballesteros et al. (1997) investigated the accuracy of haptic symmetry detection in 2D raised line stimuli and 3D objects. The task was explicit symmetry detection using one finger from one hand or using two fingers from two hands. Performance exploring unfamiliar 2D displays was poor, especially when participants explored the stimuli with just with one finger. Ballesteros and colleagues suggested that bimanual exploration was superior because the inputs from the two fingers allowed the parallel extraction of shape information and, at the same time, they provided the body midline to be used as body-centred reference frame. In addition, symmetry detection for 3D objects was more accurate than for 2D stimuli. Ballesteros and colleagues explained these results by suggesting that 3D objects offered more informative exploration (enclosing exploratory procedures rather than just contour following)¹ which increased the availability of reference information, thus improving symmetry detection.

In a subsequent study, Ballesteros et al. (1998) used an implicit task in which half the stimuli were closed shapes and half were open. Participants had to haptically explore these stimuli and detect whether the shape was open or closed, with half the stimuli symmetrical and half not in both cases. Ballesteros et al. (1998) reported that, by providing an efficient reference frame, in this case by aligning the axis of symmetry of the stimuli to the body midline and exploring the stimuli with the two index fingers, symmetry could be encoded incidentally by haptics. The presence of symmetry improved performance on the spatial task, similar to the incidental coding of symmetry which has been found to occur for vision (Wagemans, 1995). Orientation of the axis of symmetry of the stimuli was also manipulated in their three haptic experiments. The presence of symmetry only influenced performance when the objects were aligned to the body midline of the participants, and not when the axis of symmetry of the stimuli ran across the body midline or was oriented obliquely. This suggests that haptics requires aligned axes to encode

symmetry implicitly. Here, both the body midline and the axis of the exploring hands are aligned to the axis of symmetry of the stimulus. In contrast, in explicit symmetry detection tasks, the hands may be rotated to fit the axis of symmetry of the objects, so participants may still be able to detect symmetry for non-aligned orientations though symmetry detection here may nevertheless be harder than for aligned stimuli.

Ballesteros and Reales (2004) manipulated stimulus height along the z-axis, keeping constant the shape, size and complexity of stimuli. They compared explicit haptic symmetry detection for raised line, raised surface, 3D short objects and 3D tall objects. Supporting the reference hypothesis (Millar, 1994), their results showed that performances improved with the height of the stimuli (see also Lawson & Bracken, 2011) and with bimanual exploration. Specifically, exploration using both hands aligned with the body midline, facilitated the detection of symmetry. However, orientation of the axis of the object was not manipulated so it is not clear whether this bimanual alignment advantage was caused by the nature of exploration (using one versus two handed) or by matching the axis of symmetry of exploration to the axis of symmetry of the stimulus (since all stimuli were aligned with the body midline). In addition, none of these studies by Ballesteros and colleagues manipulated the position of the object in relation to the body of the participants; stimuli were always presented directly in front position of the participant.

In summary, symmetry detection by haptics seems to be easier with bimanual exploration of objects placed in front of the observer's body midline with the axis of symmetry of the object aligned to the body midline (e.g., Ballesteros et al., 1998). This positioning would provide an effective and salient reference frame about which spatial information could be encoded (Millar, 1994). The advantage offered by this combination of positioning and alignment has been supported by several haptic studies (Ballesteros et al., 1997; Ballesteros et al., 1998; Ballesteros & Reales, 2004; Cattaneo et al., 2010; Cattaneo et al., 2013; Cecchetto & Lawson, in press; Lawson et al., in press; Locher & Simmons, 1978; Millar, 1978, 1994). However, there are multiple reference frames through which we can encode objects (Volcic, Wijntjes and Kappers, 2009). Vision, for example, can encode information about an object using allocentric (environment-centred) or retinocentric, head-centred or

body-centred (egocentric) reference frames. In most studies of haptic perception, stimuli are placed in front of and in line with participant's body midline, so stimuli are aligned with both the natural symmetry of the body midline and the symmetrical positioning of the hands. Thus the frame of reference associated with the advantage for detecting symmetry in this position could be either body-centred or hand-centred or, indeed, both reference frames might be used.

To investigate this issue, in the present study, we manipulated both object position relative to the body (in front versus on the right side) and orientation of the axis of symmetry of the object (aligned with or running across the body midline). Variation in object position would change the object's representation in a body-centred reference frame whilst variation in the orientation of the axis of symmetry would change the object's representation in a hand-centred reference frame. The aim was to test whether symmetry haptic detection relies exclusively on one of these two reference frames or whether a combination of both influences performance.

As far as we are aware, no previous haptic experiment investigating symmetry detection has systematically manipulated object position relative to the observer. However, in a series of relevant studies, Kappers (2004, 2007) investigated haptic perception of parallelism between bars placed in the horizontal, midsagittal and frontoparallel planes. Blindfolded participants were required to match the orientation of a reference bar by rotating a second, test bar at different locations.

Kappers (2004, 2007) reported large and systematic deviations in how well participants could match the orientation of the bars and she proposed that these results suggested that a hand-centred reference frame was used as the primary reference frame for spatial coding, rather than a body-centred reference frame. In contrast, a number of haptic object recognition studies suggest that body-centred and head-centred reference frames may be important when objects are being identified. Lawson, Boylan and Edwards (2013) manipulated hand and gaze positions and tested 2D and 3D object recognition using the right hand. They found that directing the head to look towards the exploring hand improved object recognition, but only when the exploring hand felt the object in an anatomically unusual location, crossing the

participant's body midline, and not when the exploring hand was on the usual side of the midline. In another object recognition study, Lawson (2014) reported that participants could use their hands to successfully identify familiar objects explored at their side and behind their back as efficiently as those explored in the usual front position. These studies highlight the importance of the object position relative to the head and to the body midline as factors affecting haptic perception. Together these results suggest that haptics may not rely on a single, spatial reference frame, but that different egocentric frames (head-centred, body-centred and hand-centred) might all be used depending on the task (Kappers, 2013; Lawson, 2014; Lawson et al., 2013). It is therefore an open question which reference frame is used for haptic symmetry detection.

In summary, in the explicit symmetry detection task with two-handed exploration reported here we investigated whether the reference frame used was body-centred or hand-centred by varying both the orientation of the axis of symmetry and the position of the object. Novel, 3D objects were presented individually in front, or on the right side, of participants. One group felt objects with their axis of symmetry aligned with the participant's body midline and another group felt objects with their axis of symmetry rotated by 90° clockwise to run across the participant's body midline. Our choice to use 3D novel objects was motivated by two points. First, 3D objects (rather than 2D objects) are optimal stimuli for haptics because they allow extra exploration strategies, providing informative depth cues which have been shown to aid object recognition (Lawson & Bracken, 2011) and symmetry detection (Ballesteros et al., 1997; Ballesteros & Reales, 2004). Second, we used novel objects so that people could not just rely on stored knowledge about an object to do the task and because few familiar objects are asymmetrical.

7.2.1 Method

7.2.1.1 Participants

There were 32 participants (20 females, mean age = 24.2 years, s.d. = 4.5, range 18-34). 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. The study received ethical approval from the local ethics committee.

7.2.1.2 *Materials*

A set of 24 pairs of 3D novel objects were hand-crafted using combinations of parts of everyday, plastic objects. One of each pair was symmetrical along one axis. The other was identical to the symmetrical object except that some parts were moved to break the overall symmetry of the shape, see Figure 1. The stimuli varied in size from 2.5cm - 38cm wide, 4.5cm - 20cm long and 0.7cm - 21.5cm high. In addition to these 48 experimental stimuli a further 6 pairs of filler objects were created in the same way. These filler objects were duplicates of six of the experimental pairs and were included to disrupt the regularity of the trial order, as detailed in the Design section. Finally, three further pairs of novel objects were created in the same way and were used as practice items.

To ensure a uniform surface and to reduce texture defects, each object was spray-painted in glossy grey and then it was glued onto a white ceramic tile (15cm x 15cm). Having the object on a tile ensured its stability and prevented rotational and lifting movements by the participant during exploration. A piece of tape (green for symmetrical objects and blue for asymmetrical ones) was attached to each tile (Figure 1) to serve as a shape and axis orientation reference for the experimenter. The objects were placed directly in front, or on the right, of the participant, with the tape oriented to be aligned or across (rotated by 90° clockwise) the participants' body midline (see Figure 1).

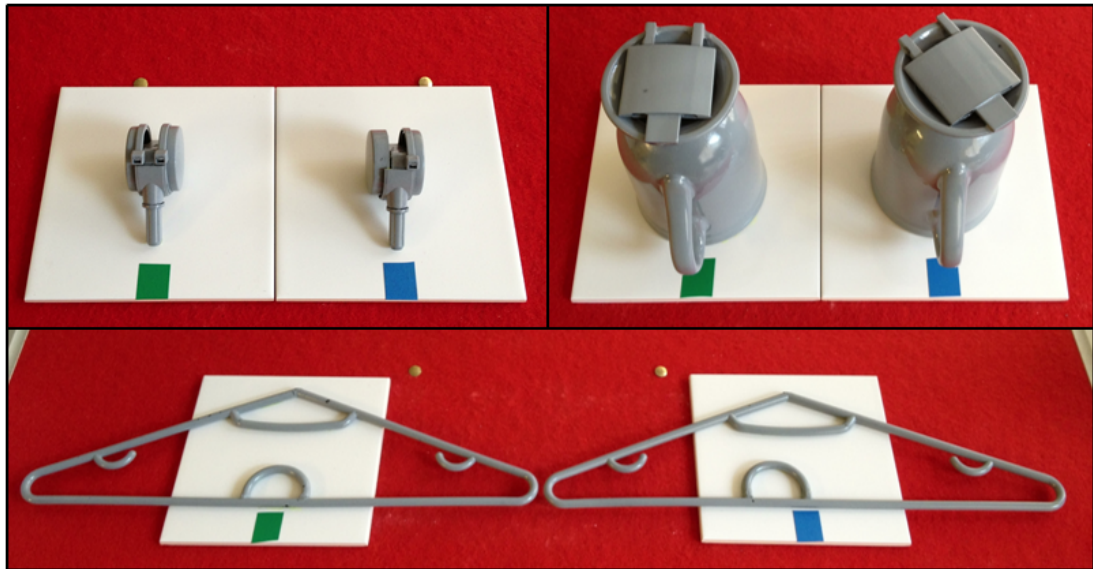


Figure 1. Examples of the stimuli used in Experiment 1. Each picture shows a pair of 3D novel objects with the symmetrical object on the left (with green tape on the tile) and the asymmetrical object on the right (blue tape). Participants wore a blindfold throughout the experiment.

7.2.1.3 Design

Each participant completed 54 trials (48 experimental trials and six filler trials). Each of the 48 experimental objects was presented once with position of the object (in front of, or on the right side of, the participant) and presentation order (forward or backward) counterbalanced across participants. Participants were randomly divided into two groups: 16 felt objects with the axis of symmetry of the object aligned with their body midline and 16 with the axis running across their body midline. Within each group, half of the objects were presented in front of the participants and the other half on their right side. For both positions, half of the objects were symmetrical and half were asymmetrical. Stimuli were presented in one fixed order to half of the participants and in the reverse order to the other half. Presentation order for the first 24 experimental trials was pseudo-randomized so that no more than three successive trials had the same response or the same position, and so that only one object from each matched pair was presented to a given participant. After the first 24 experimental trials, the remaining 24 experimental trials and six filler trials were presented. The experimental trials presented the same 24 objects but with shape (symmetrical or not) and object

position (front or right side) both changed. Thus, for example, if symmetrical object 1 was presented in the front position in the first subblock of 24 experimental trials, the asymmetrical version of object 1 was presented on the right side in the remaining subblock of 24 experimental trials. The same presentation order was used in both sets of experimental trials apart from the first two objects of these trials (25th and 26th objects) which were reversed. The six filler trials were added after the fourth trial of the second set of 24 experimental trials (28th object). These filler objects were included to reduce the likelihood that participants realised that the objects were repeated in the two experimental subblocks. This design resulted in eight different trial lists with shape (symmetrical or asymmetrical), object position (front or right side) and trial order (forward or backward) all fully counterbalanced for both groups of participants (aligned and across). Two participants per group were assigned to each trial list.

7.2.1.4 Procedure

Before starting the experiment, participants were instructed about the symmetry detection task that they were going to perform and about the orientation of the axis of symmetry (aligned or across their body midline) of the objects. Participants were instructed outside the lab and were then blindfolded using a black mask and guided inside the lab by the experimenter. They were seated in front of a desk and a second desk was placed on their right side, see Figure 2. Both desks were 70cm high and textured 30cm x 40cm carpet mats were placed on them so that the objects on tiles did not move as the objects were explored.

Objects were placed at the centre of the mats. The distance from the centre of the object to the participant's body was approximately 40cm. Two textured, circular patches were attached at the two corners of the mat nearest the participant. These patches served as the resting positions for their left and right hands between trials. A microphone was used to detect the participant's vocal responses. It was placed 110cm above the floor, suspended between the two desks and was connected to a PC running Windows 7 and EPrime 2.

On each trial the experimenter told the participant whether the object was going to be placed in front of them or on their right side, and the participant placed their hands in the appropriate resting positions. Participants were told to explore the objects with both hands and they were instructed not to move, rotate or pick up the stimuli. During exploration they had to keep their head pointing forward but they were allowed to slightly rotate their body to facilitate right side exploration.

After positioning the object, the experimenter triggered a warning beep, followed by an auditory 'go now' signal which indicated to the participants that they could start exploring the object. Participants were instructed to respond saying 'symmetric' or 'not' as quickly and accurately as possible. Their response time (RT) was taken from the onset of the 'go now' signal until their vocal response. The experimenter then typed in their response and a high or low or pitched sound was provided as feedback for correct and error responses respectively. The experiment took around 40 minutes.

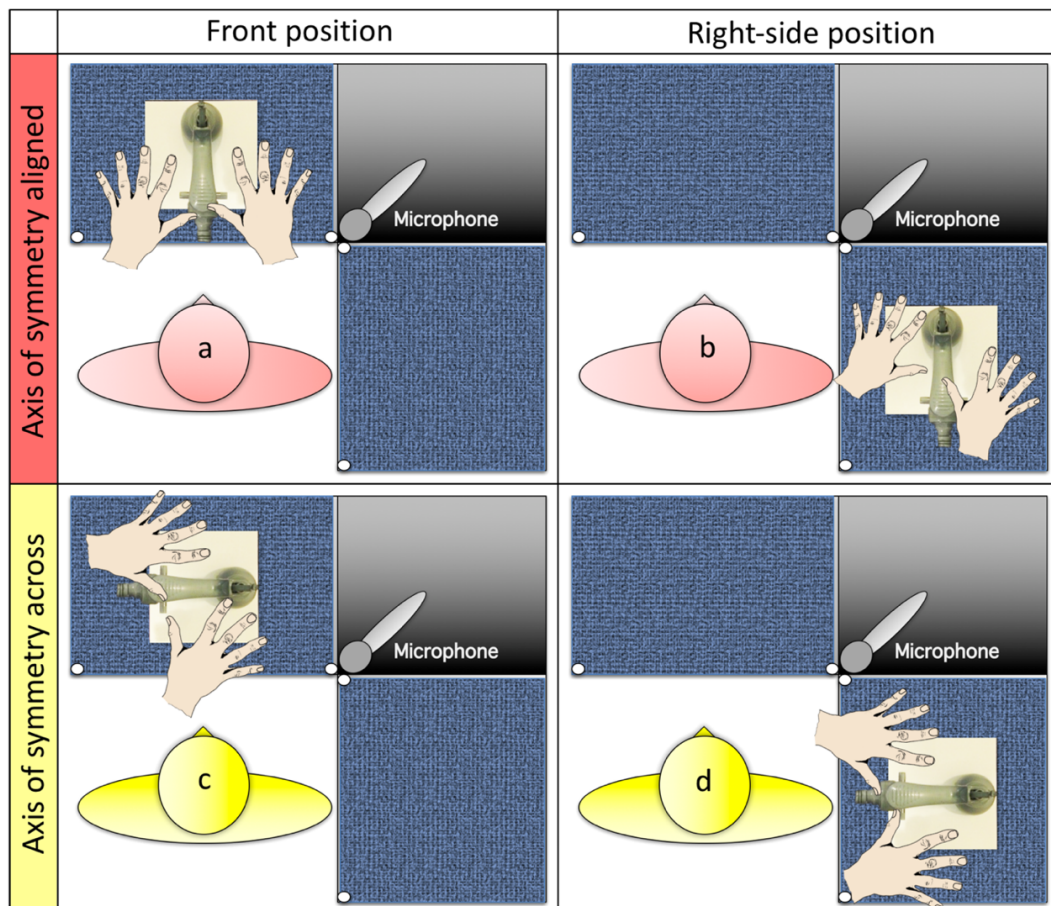


Figure 2. Schematic representation of the four experimental conditions showing the same symmetrical object in each case. The top, red row shows the two aligned-group

conditions for the front (left) and right (right) object positions. The bottom, yellow row shows the two across-group conditions for the front (left) and right (right) object positions. Each object was presented individually and the white dots on the mats show the resting positions for the hands.

7.3 Results

Three participants did not fully understand the task and were replaced as their performance was close to chance. Correct RT faster than 1s or slower than 90s were removed as outliers (4.5% of the trials). Filler trials were not analysed. Analyses of variance (ANOVAs) were conducted on the mean correct RT and percentage of errors for symmetrical trials only, for consistency with reporting in previous studies, and because performance on asymmetrical trials is difficult to interpret theoretically. In the ANOVAs there was one within-participants factor of object position (front or right) and one between-participants factor of the orientation of the object's axis of symmetry (aligned or across) relative to the participants' body midline.

Object position was not significant for RT [$F(1,30) = .05$, $p = .826$, partial $\eta^2 = .00$] but it was for errors [$F(1,30) = 9.55$, $p = .004$, partial $\eta^2 = .24$]. Symmetry was detected more accurately for objects presented in front (16.2s, 24% errors) rather than on the right side (15.8s, 28%). The axis orientation was not significant for RT [$F(1,30) = .51$, $p = .48$, partial $\eta^2 = .02$] or for errors [$F(1,30) = .56$, $p = .462$, partial $\eta^2 = .02$]. Symmetry detection was similar for aligned (17.3s, 18%) and across (19.7s, 20%) axis orientations. The interaction of object position \times axis orientation was not significant for RT [$F(1,30) = .98$, $p = .329$, partial $\eta^2 = .03$] but it was for errors [$F(1,30) = 5.65$, $p = .024$, partial $\eta^2 = .16$], see Figure 3. Post-hoc Newman-Keuls analyses ($p < .05$) revealed that symmetry was detected more accurately for objects positioned in front with an aligned axis (12%) compared to objects positioned in front with an across axis (19%), or to objects positioned on the right with either aligned (24%) or across (21%) axes, with no significant differences between these latter three conditions.

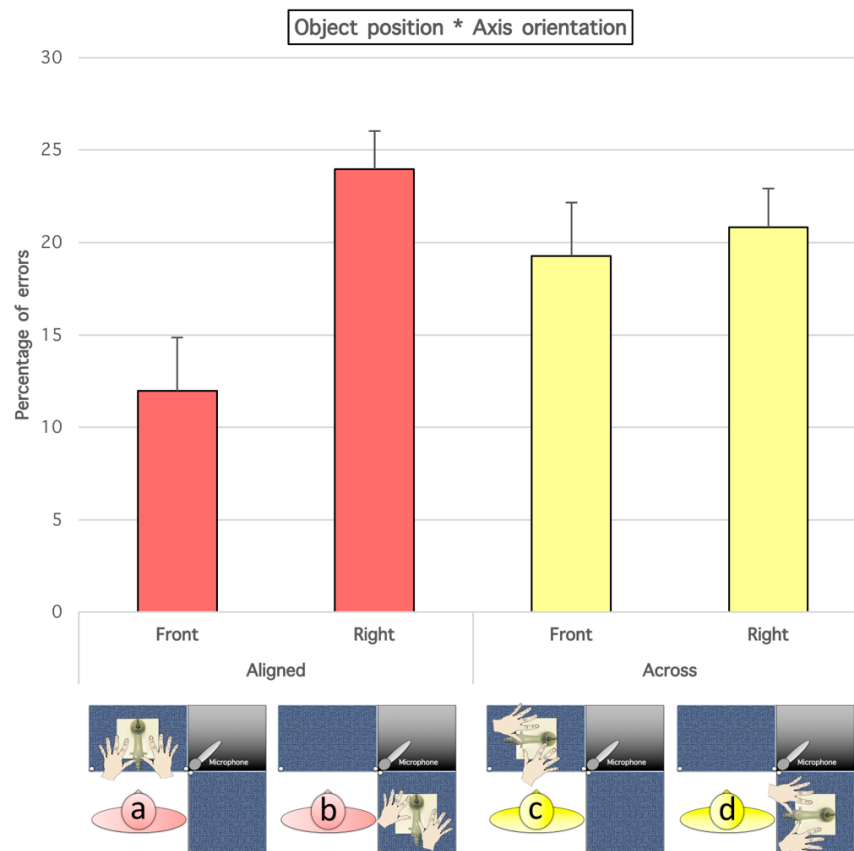
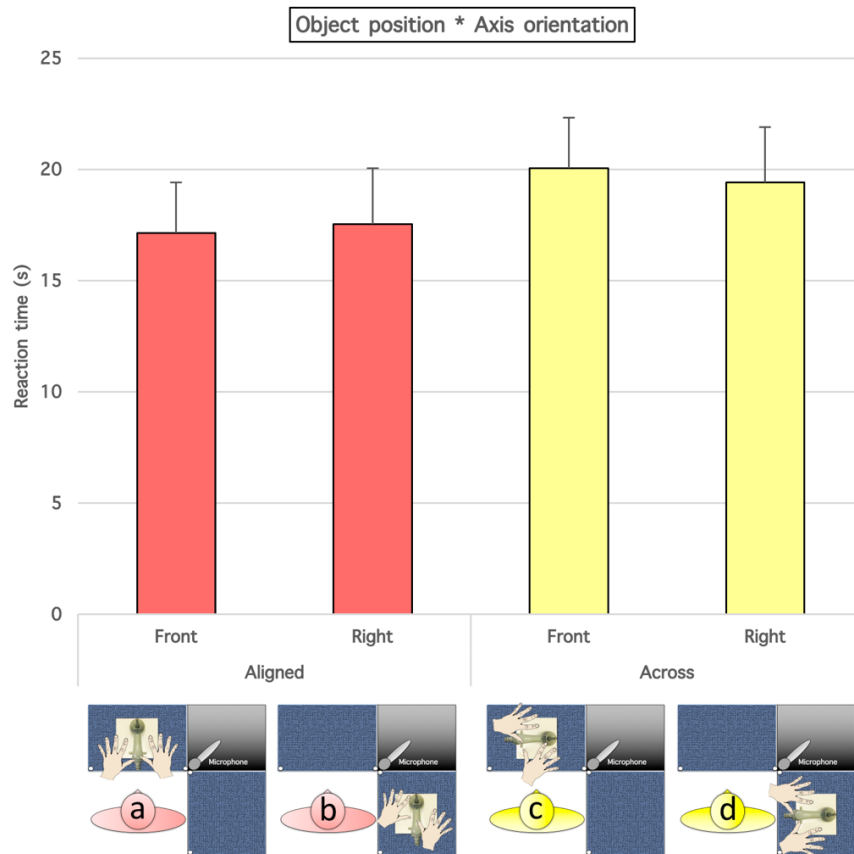


Figure 3. Results for RT (top) and percentage of errors (bottom) for the haptic detection of symmetry in 3D novel objects presented with their axis of symmetry aligned with

(red bars) or running across (yellow bars) the participants' body midline, and positioned in front or on the right side of the participant. Error bars represent one standard error of the mean. Icons at the base of each bar schematically represent the four experimental condition (a, front-aligned; b, right-aligned; c, front-across; d, right-across) and match those shown in Figure 2.

7.4 Discussion

In haptic symmetry perception, exploring objects with two hands has been shown to improve symmetry detection compared to single hand exploration. In this situation, both hand movements and spatial information can be coded efficiently in relation to the body midline (Ballesteros & Reales, 2004). Here, we investigated the role of reference frames in explicit symmetry perception by haptics. The reference frame hypothesis suggests that bimanual exploration allows participants to relate the position of their hands to their own body midline, providing an effective spatial reference for coding the presence of symmetry in external objects (Millar, 1994).

The present study tested whether the object must be presented in front of the participant for the axis alignment advantage to occur. Our results show that explicit symmetry detection using the two hands is uniquely privileged when objects are positioned in front of the participant and with their axis of symmetry aligned to the participant's body midline, consistent with previous research (e.g., Ballesteros et al., 1997). We compared performance here to other conditions when the object was rotated so the axis of symmetry ran across the body midline (which has been tested before) but also when the object position was changed to be at the side of the participant (which has not previously been tested). We found that only when objects were both placed in front and their axis was aligned to the body midline could the body-centred reference frame be used efficiently. This result contrasts to the findings of Kappers (2007) who argued in favour of a hand-centred reference frame being the most important egocentric reference frame using results from a parallelity matching task. This difference suggests that the reference frame used to encode spatial relations may differ across tasks. For symmetry detection tasks using 3D novel objects, a combination of reference frames seems to be used (both hand-centred and

body-centred), perhaps because more complex information needs to be represented to detect symmetry as opposed to parallelity.

One limitation of the present study concerns the manipulation of object position. We found that symmetry was more accurately detected when aligned objects were presented in the front rather than on the right side of the participants' body. This result might reflect effects of reference frame, as we have suggested, but it could also depend on familiarity in exploration style. In everyday life, we generally interact and manipulate objects in front of us.

Furthermore, although there are examples of object interactions from side positions, such as moving a mouse on a computer, or changing gear while driving a car, these tasks usually do not require fine processing of shape as is required for symmetry detection. Thus since we have more experience of manipulating objects in front of us, and since exploration at other positions may feel more awkward, this may have influenced our results. However, Lawson (2014) found no advantage for object recognition for frontally positioned objects relative to objects placed on the right side or behind participants (indeed, performance was best for identifying objects on the right side). This suggests that familiarity of the object position for haptic exploration, and other factors such as the relative awkwardness of exploration of objects placed at the side or behind, may not be important factors for haptic processing.

Anatomical mechanics of the arm could partly explain our results. The specific movements of the joints of the arm (wrist, elbow, shoulder) are very different during frontal compared to side exploration. In the front position, detecting symmetry might be facilitated by the symmetrical movements of the joints, whereas in the side position the exploration of symmetrical stimuli would necessarily be asymmetrical due to the joints' mechanics. However, although arm anatomy could explain the overall frontal advantage it cannot explain the lack of difference between the aligned and across orientation in the frontal position.

A final point which should be considered is the role of head position. We are among the few animals which are capable of smooth pursuit eye movements and this allows us to track the movements of our hands more easily (Land, 1992). Aligning the head with the hands may matter for certain haptic tasks. In the current study, participants always looked forwards and so

the head and gaze was directed away from the hands exploring the object when it was placed in the right position. This may have disadvantaged this position. This possibility remains to be tested in future research, which could experimentally manipulate head position. However, note that performance here was similar for the front, across objects and the right, across objects (see Figure 3), suggesting that, by itself, misaligned head and gaze direction with hand orientation did not disrupt performance.

In summary, the current study provided evidence of the significant role of object position and axis orientation in haptic symmetry detection. These results suggest that a combination of two reference frames, body-centred and hand-centred, are together used to encode spatial relations during haptic symmetry detection using both hands. We speculate that, for an object positioned in front of the body with its axis of symmetry aligned to the body midline, bimanual exploration is uniquely effective at encoding spatially accurate representations. This is because, in this situation, the reference frames centred on both the body midline and on the hands provide consistent spatial information. This may aid haptic shape perception by minimising conflict and ambiguity in the coding of spatial relations.

Footnotes

1 Enclosure and contour following are two of the eight stereotyped haptic exploratory procedures defined by Lederman and Klatzky (1987). These two exploratory procedures are used to obtain information about global and exact shape respectively, with both procedures used to extract shape information from 3D objects but with contour following relied on exclusively for 2D objects (Lawson & Bracken, 2011). The other hand movements and properties which Lederman and Klatzky (1987) described are lateral motion (to assess texture), static contact (temperature), pressure (hardness), unsupported holding (weight), part motion test (part motion) and function testing.

Chapter 8

8 ‘It feels symmetrical. I like it!’ Exploring implicit effects of symmetry in haptic and visual preference tasks using 3D novel objects.

* This study is in preparation for submission as: Cecchetto, S & Lawson, R. It feels symmetrical. I like it! Exploring implicit effects of symmetry in haptic and visual preference task using 3D novel objects. (In preparation)

8.1 Abstract

We can use haptics (our sense of active touch) as well as vision to collect information from the environment that can be used for object and scene perception and which can also influence preference (Carbon & Jakesch, 2013). One property that is known to affect preference is bilateral symmetry. For vision, symmetry is readily detected and is often preferred. Haptics can also detect symmetry, but it is not known whether symmetry influences judgements of haptic preference. This was investigated in the present experiment. Participants felt or saw pairs of matched, 3D novel objects. One object from each pair was symmetrical and the other had some parts changed to make it partly asymmetrical. Objects were presented with their axis of symmetry either aligned with, or running across, the body midline. Symmetry and axis orientation were not mentioned to the participants, who simply chose their favourite object from each pair. For both visual and haptic presentation, we found an implicit preference for symmetry that was independent of axis orientation. Thus, although axis alignment with the bilateral symmetry of our own body and our movements makes explicit symmetry detection easier for

both vision and touch (Cecchetto & Lawson, in preparation; Cecchetto & Lawson, in press), axis alignment did not enhance the haptic preference for symmetry.

8.2 Introduction

In everyday life we use our senses to help us choose which of a set of similar objects we prefer. For example, when choosing a watermelon at the supermarket we often perform a series of tests to evaluate which fruit to pick. We evaluate its shape, its colour, its smell, and the sound it produces when knocking on its surface. From these tests we typically pick the melon that best satisfies our senses and that, hopefully, will in turn satisfy our sense of taste! When performing such tasks, we are usually able to simultaneously employ multiple sensory modalities, such as vision, touch, smell, taste and hearing. This multisensory input presumably helps us to make effective preference choices.

However, there are also times when we must make choices between items based on information from one modality in isolation. For example, valuable products in shops are often kept behind the counter so we cannot touch them, and when we do online shopping we have to make choices based solely on pictures. In both cases we therefore rely on vision alone. Unisensory choices do not always rely on vision: prizes in lucky dip contests at fairs are sometimes kept out of sight and we must use our sense of touch alone to choose them. Thus, an interesting question that inspired this study was whether our sense of active touch alone would produce the same preference judgments for a set of objects as the preference judgements for vision alone. Both vision and touch are expert at recognizing the shape of objects (e.g., Lawson, 2009; Lawson & Bracken, 2011; Lederman & Klatzky, 1987) and at detecting spatial properties including regularities such as symmetry and repetition (e.g., Cecchetto & Lawson, in press; Lawson Ajvani & Cecchetto, in press). Here, we investigated whether novel 3D objects were preferred when they were had more bilateral (mirror-reflectional) symmetry.

The world is full of symmetrical 3D objects, including each of the three natural kingdoms of minerals (e.g., crystals), plants (e.g., leaves) and animals

(e.g., human faces). From art to architecture, visual symmetry has often been connected to the concept of beauty, perhaps due to its link to the natural world, and symmetry is thought to have a major influence on aesthetic preference (Ramachandran & Hirstein, 1999). Anatomical symmetry, for example, is a cue for mating preference in several species (Tyler, 1995) which may explain why symmetrical faces are perceived as more attractive than asymmetrical faces (e.g., Cárdenas & Harris, 2006; Gangestad, Thornhill & Yeo, 1994; Thornhill & Gangestad, 1993, 1999). It is therefore not surprising that we are so sensitive to symmetry (for reviews in vision, see Giannouli, 2013; Treder, 2010; Tyler, 1995; van der Helm, 2014; Wagemans, 1997). Importantly, we are also able to discriminate symmetry with our hands (for a recent haptic review, see Cattaneo, Bona, Bauer, Silvanto, Herbert, Vecchi & Merabet, 2014).

Many empirical studies have found that visual symmetry is a powerful predictor of human preference, even for abstract, geometrical patterns (Eisenman, 1967; Eisenman & Gellens, 1968; Jacobsen & Höfel, 2001, 2002; Jacobsen, Schubotz, Höfel & van Cramon, 2006; Tinio & Leder, 2009), and for implicit preference (e.g., Makin, Pecchinenda & Bertamini, 2012). This may occur because visual symmetry is part of the early, automatic encoding processes of shape, and also because symmetry influences later, attentional processes (e.g., van der Helm & Leeuwenberg, 1996; Wagemans, 1995). Specifically, our aesthetic preference for symmetry may arise from symmetrical stimuli being easier to process, perhaps because they include less information than non-symmetrical stimuli. Garner (1974) reported that judgments of figural goodness were indirectly proportional to the amount of information that observers had to extract to perceive the figure, consistent with the perceptual fluency hypothesis. This states that positive aesthetic responses towards objects are a function of the fluency with which objects can be processed (Reber, Wurtz & Zimmermann, 2004). However, the amount of information needing to be processed cannot be the only factor influencing aesthetic judgments because ratings of figural goodness vary with orientation, with vertical configurations preferred to horizontal ones which, in turn, are preferred to oblique ones, yet stimuli differing only in orientation have the same amount of information (Palmer, 1991). Furthermore, the perceptual fluency hypothesis has not always been supported. Some authors reported

that slight asymmetries of objects in art are experienced as more interesting (McManus, 2005) and people prefer slightly asymmetrical faces to perfectly symmetrical, computer generated faces (Zaidel & Cohen, 2005; Zaidel & Deblieck, 2007).

Moving from vision to our sense of active touch, despite the undoubted importance that aesthetic attributes of touch have on our quality of life, there is surprisingly little empirical research on this topic (Essick, McGlone, Dancer, Fabricant, Ragin, Phillips, Jones & Guest, 2010). Moreover, most extant research has investigated passive, tactile stimulation (e.g., McGlone, Wessberg & Olausson, 2014) rather than aesthetic responses to active, haptic inputs (Carbon & Jakesch, 2013). For example, Ekman, Hosman and Lindstrom (1965) reported preferences were proportional to the softness of various sandpapers, cardboards, and papers, whilst Hilsenrat and Reiner (2011) showed that softer and smoother surfaces were preferred, whilst Jakesch and Carbon (2011) reported a preference for rounded objects. It has been established that the ability to handle objects can positively influence attitudes towards the object (Grohmann, Spangenberg & Sprott, 2007; Peck & Childers, 2003a, 2003b). As far as we are aware, only one study (Schmalzer, 2014, described below) has investigated whether haptics shows a preference for symmetry.

It is known that symmetry can be encoded incidentally by haptics because it can implicitly affect haptic shape processing (Ballesteros, Millar & Reales, 1998). Ballesteros and colleagues presented small, 2D shapes and asked participants to decide whether each shape was open or closed. Half of the shapes were symmetrical and the other half was not. Their hypothesis was that if symmetry was encoded automatically then it should facilitate the shape processing task. Symmetry facilitated visual performance of the task but had no effect on haptics when only one finger was used to explore the stimuli. However, using two fingers aligned to the participants' body midline produced an advantage for detecting symmetrical open shapes. Here, symmetry aided performance when it was could be detected using symmetrical body movements aligned with both the body midline and the axis of symmetry of the object. Ballesteros et al. (1998) suggested that in this case symmetry was used by haptic processes because it could be encoded using a salient, body-centred spatial reference frame.

In the present study, we extended the work of Ballesteros and colleagues to investigate whether symmetry could be encoded implicitly to affect haptic aesthetic preference. To test this, we simultaneously presented pairs of 3D, novel objects to be explored haptically. The objects were always placed in front of the participant, on two shelves, one on top of the other. Objects within each pair were largely composed of the same parts and had the same texture but one object was perfectly symmetrical and whilst some parts were changed in the other object to make it asymmetrical. Participants were not told that the objects could be symmetrical; they were simply told to explore the two objects freely, for as long as they wanted and in any way they wanted, using either one or two hands, and to choose which they preferred. We used novel objects because, for familiar objects, pre-existing, semantic, visual and name information might have influenced performance.

We manipulated perceptual processing fluency by presenting objects with their axis of symmetry either aligned with, or running across, the participants' body midline. We expected symmetry to be more salient to haptics, and therefore to be more strongly preferred, when the objects were aligned to the body midline. This was because, as explained below, bimanual exploration might then be more likely to be symmetrical about the body midline making it easier to build up a symmetric perceptual representation of the object (Ballesteros et al., 1997; Ballesteros & Reales, 2004; Cecchetto & Lawson, in preparation). Participants were not told about the axis manipulation and this varied from trial to trial. We therefore did not expect them to systematically adjust their hands to explore the objects symmetrically relative to the object's axis of symmetry. Instead, we expected them to tend to explore each object in a more natural way by moving their hands symmetrically in alignment with their body midline. If so, then symmetry was expected to be less salient for objects with the axis oriented across, rather than aligned with, their body midline and this, in turn, was expected to result in lower judgments of preference for axis-across objects.

The only similar research we are aware of to our experiment was a study by Schmalzer (2014). Schmalzer examined whether judgments of pleasantness and interestingness varied across three levels of symmetry (perfect, partial and random). Schmalzer used 2D planar wooden triangles glued onto cardboard and did not manipulate stimulus alignment. He found

that perfectly symmetrical triangles were preferred over partially symmetric and asymmetric triangles, consistent with the visual study by Gartus and Leder (2013), and suggesting an influence of symmetry on haptic aesthetics.

8.2.1 Method

8.2.1.1 Participants

There were 16 participants (11 females, mean age = 20.7 years, s.d. = 3.5, range 18-28). They were either volunteers or undergraduate students from the University of Liverpool who participated for course credit. All the participants had normal or corrected to normal vision and self-reported as right-handed, with no known conditions affecting their sense of touch.

8.2.1.2 Materials

A set of 24 pairs of 3D novel objects were hand-crafted using combinations of parts of everyday, plastic objects. One of each pair was symmetrical along one axis. The other was identical to the symmetrical object except that some parts were moved to break the overall symmetry of the shape, see Figure 1. The stimuli varied in size from 2.5cm - 38cm wide, 4.5cm - 20cm long and 0.7cm - 21.5cm high. In addition to these 48 experimental stimuli a further 6 pairs of filler objects were created in the same way. These filler objects were duplicates of six experimental pairs and were included to disrupt the regularity of the trial order, as detailed in the Design section.

To ensure a uniform surface and reduce texture defects, each object was spray-painted in glossy grey and then it was glued onto a white ceramic tile (15cm x 15cm), see Figure 1. Having the object on a tile ensured its stability and prevented rotational and lifting movements by the participant during exploration. A piece of tape (green for symmetrical objects and blue for asymmetrical ones) was attached to each tile (Figure 1) to serve as an axis orientation reference for the experimenter. The objects were placed directly in front of the participant, with the tape oriented to be aligned or across (rotated by 90° clockwise) the participants' body midline (see Figure 1).

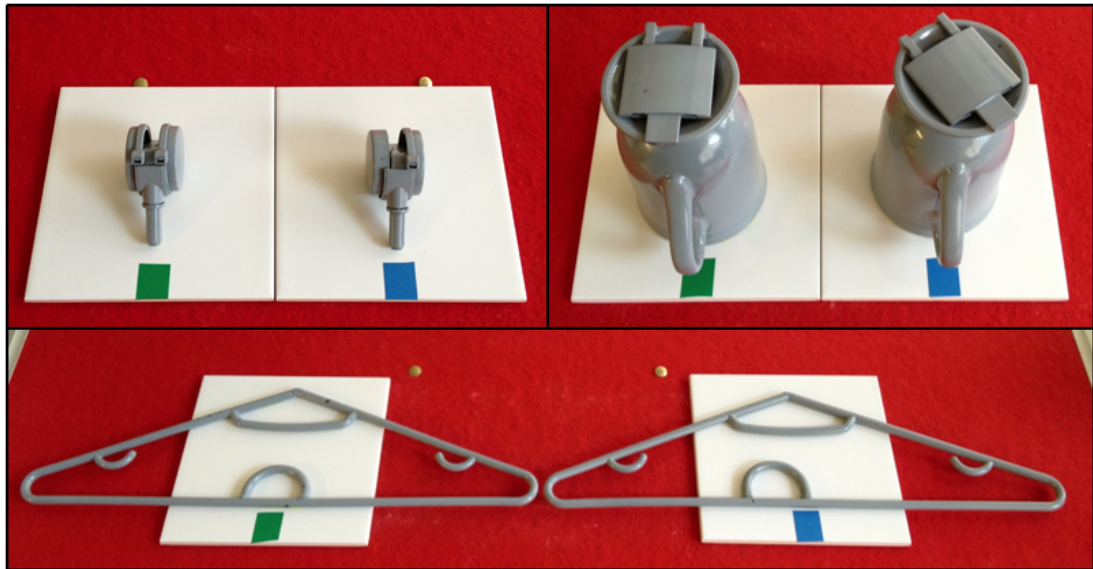


Figure 1. Examples of the stimuli used in Experiment 1. Each picture shows a pair of 3D novel objects with the symmetrical object on the left (with green tape on the tile) and the asymmetrical object on the right (blue tape). Participants wore a blindfold throughout the experiment.

8.2.1.3 Design

The experiment comprised a haptic block of trials followed by a visual block of trials with 54 trials per block (48 experimental trials and six filler trials) and no practise trials. Modality order was not varied because we wanted to investigate implicit haptic symmetry detection and, for visual presentation, we expected participants to notice that the difference between the pairs of matched objects was the presence of symmetry. On each trial, two matched objects were presented, one symmetric and one asymmetric. Stimuli were always presented in the front of the participant, on two shelves, one on top of the other and both the objects were presented at the same axis orientation. Shelf position (symmetric object on the top or bottom), the orientation of the axis of symmetry of the objects (aligned with, or running across, the participants' body midline) and presentation order (forward or backward) were fully counterbalanced across participants. To achieve this, we created eight trial lists in which object presentation was pseudo-randomized to ensure that a maximum of three successive trials had symmetrical objects on the same shelf or at the same axis orientation. All of the pairs of objects were presented in the first 24 trials. The remaining 24 experimental trials and six filler trials

were then presented. This second half of experimental trials presented the same 48 objects as the first half of experimental trials but with position of the symmetrical object (top shelf or bottom) and object axis (aligned or across) both changed. Thus, for example, if the symmetrical version of object 1 was presented on the top shelf at the across orientation in the first subblock of 24 experimental trials (with the asymmetrical version of object 1 on the bottom shelf at the across orientation), then the symmetrical version of object 1 would be presented on the bottom shelf at the aligned orientation (with the asymmetrical version of object 1 on the top shelf at the aligned orientation) in the second subblock of 24 experimental trials. The same presentation order was used in both sets of experimental trials apart from the first two objects of these trials (25th and 26th objects) which were reversed. The six filler trials were added after the fourth trial of the second set of 24 experimental trials (28th object). These filler objects were added to reduce the likelihood that participants noticed that the pairs of objects were repeated in the two experimental subblocks. Objects were presented in the same order and at the same shelf position and orientation in the haptic and the visual blocks.

8.2.1.4 Procedure

Participants were instructed about the haptic and visual preference tasks that they were going to perform and they were told that on each trial two very similar novel objects would be presented to them. They were told to fully explore each object and decide which of them they would have kept for themselves and which one they would have discarded. Neither symmetry nor axis orientation (aligned or across) was mentioned to them. Participants were seated in front of a 70cm high desk and were shown the two wooden shelves which were aligned to their body midline, and the base of each shelf was 5cm and 25cm above the desk, see Figure 2. On each trial, one object was placed, one above the other, at the centre of each shelf. In the haptic block, participants were blindfolded and told to explore the objects by touch however they wished, except that they were not allowed to move, lift or rotate the objects. An optional break was permitted between the two blocks. In the visual block the blindfold was removed and participants were not permitted to touch the

objects. Only the stimuli being presented on shelves were visible. On each trial, participants made an unspeeded verbal response of 'top' or 'bottom' to specify which of the two objects they preferred. They were told that there was no correct answer and no feedback was provided. The experiment took around one hour.



Figure 2. A blindfolded participant haptically exploring a pair of aligned objects during the first, haptic block. The symmetrical object is on the top shelf. Participants usually explored each object in turn using both hands together on the same object. However, a few participants, used one hand to explore each object so they felt both objects simultaneously, as shown by the participant here.

8.3 Results

No participants were replaced. Filler trials were not analysed. There were three within-participants factors: modality (haptics or vision), object position (top or bottom shelf) and orientation of the object's axis of symmetry (aligned or across) relative to the participants' body midline. An ANOVA was run on the mean preference for the symmetrical compared to asymmetrical objects. The only significant effect in this analysis was for modality [$F(1,15)=53.81, p < .001, \text{partial } \eta^2 = .78$]. There was a symmetry preference for both modalities but haptics showed a lower preference (60.5%) than vision (87%). Object position was not significant [$F(1,15)=.014, p = .9, \text{partial } \eta^2 = .00$], with similar preferences for objects on the top (74%) and bottom (74%) shelves. Axis orientation was also not significant [$F(1,15)=3.35, p = .087, \text{partial } \eta^2 = .18$], with similar preferences for aligned (76%) and across (71%) objects, though as predicted there was a trend for symmetry to be preferred more when the axis of symmetry was aligned with the body midline. None of the interactions were significant. For modality x object position, [$F(1,15)=.042, p = .8, \text{partial } \eta^2 = .00$]; modality x axis orientation [$F(1,15)=.219, p = .65, \text{partial } \eta^2 = .01$]; object position x axis orientation [$F(1,15)=.11, p = .75, \text{partial } \eta^2 = .01$]; and modality x object position x axis orientation [$F(1,15)=.046, p = .8, \text{partial } \eta^2 = .00$].

To check whether the implicit preference for symmetry was significantly different to chance we conducted individual one sample t-tests on the mean preference judgments for symmetrical objects relative to chance (50% preference) for both axis orientations (aligned and orthogonal) for each modality (haptics and vision). All four t-tests were significant. For haptics, for aligned stimuli (63.5%) [$t(15)=3.09, p = .007$] and across stimuli (58%) [$t(15)=2.21, p = .043$]; for vision, for aligned stimuli (89%) [$t(15)=15.50, p < .001$] and across stimuli (85%) [$t(15)=14.10, p < .001$].

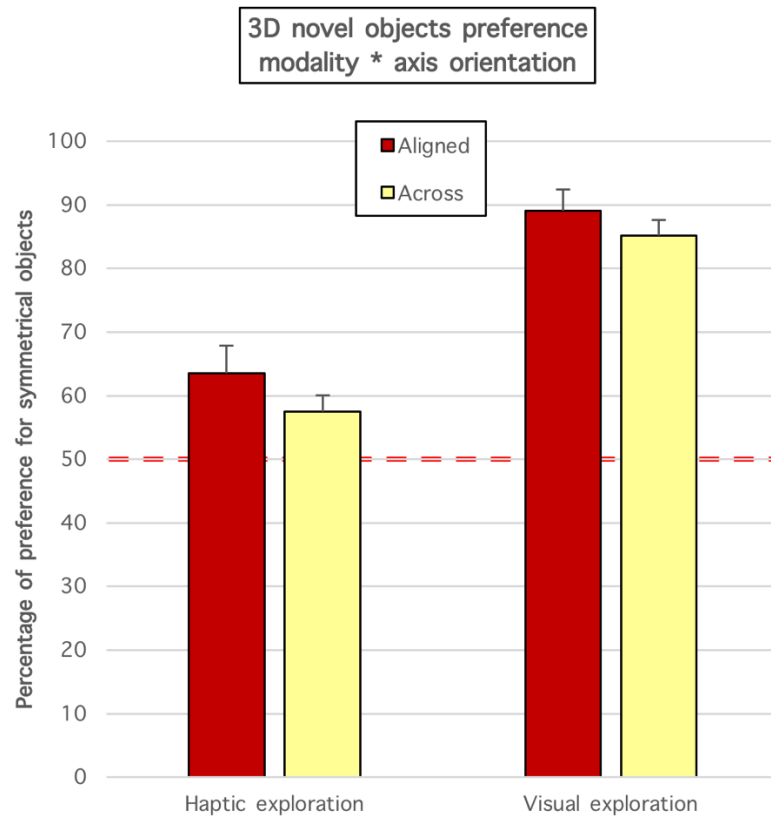


Figure 3. Percentage of preference for symmetrical relative to asymmetrical objects with the axis of symmetry aligned with (yellow bars) or running across (red bars) the participants' body midline, for haptic (left) and visual (right) exploration of matched pairs of 3D novel objects presented simultaneously in front of the participant. All four conditions were significantly different from chance, which is indicated by the red dotted line. Error bars represent one standard error of the mean.

8.4 Discussion

Preference tasks have often been used in research into vision aesthetics. Recently this interest has been extended to haptic aesthetics, which is still a young science (Carbon & Jakesch, 2013). In vision, symmetry is an important and salient feature that has been consistently linked to aesthetic preference (Ramachandran & Hirstein, 1999). Visual symmetry has often been associated with a sense of beauty and harmony and for vision symmetrical stimuli are implicitly preferred to asymmetrical ones (Pecchinenda, Bertamini, Makin & Ruta, 2014). Here, we replicated this finding of an implicit preference for visual symmetry and we extended it to show that the same set of symmetrical stimuli

were also implicitly preferred by haptics. This preference occurred although our participants were not told about the symmetry manipulation and although the haptic task always preceded the visual task. The effect for haptics extended the results reported by Schmalzer (2014). Our results show that haptic symmetry detection is sufficiently powerful to influence preference despite explicit haptic symmetry detection being quite slow and error-prone (Cecchetto & Lawson, in preparation), and despite haptic symmetry not being as salient as visual symmetry, especially in implicit tasks (e.g., Millar, 1978). One factor influencing our results may be that the simultaneous comparison of matched pairs of symmetrical and asymmetrical objects could have enhanced the salience of symmetry in this study. However, people did not seem explicitly aware that they were responding to symmetry. After completing the haptic block, most participants spontaneously said that, when they noticed a difference between the two objects, one felt more organized and better structured than the other, but no participant explicitly mentioned the term symmetry. In contrast, after completing the visual block most participants specifically mentioned that their decisions were influenced by whether an object was 'reflected', 'equal' or 'symmetrical'.

As symmetry about the vertical axis is usually more salient than it is about the horizontal and oblique axes (e.g., Wagemans, 1997), we had expected symmetry to be more salient when the axis of symmetry of the object was aligned with, rather than running across, the body midline, because in this orientation the object's axis of symmetry fitted with the symmetry of the participant's own body. However, contrary to our expectations, preference for symmetry was not significantly greater for aligned relative to across objects. There was, though, a trend in that direction for both haptic and visual presentation and it is possible that this effect would be obtained in a larger-scale study.

In summary, the results of this exploratory study showed that symmetrical versions of 3D novel objects were preferred for both modalities even when participants were not encouraged to attend to symmetry. This finding shows that beauty is not only in the eyes of the beholder, as is commonly claimed, but to some extent, is also in the hands of the beholder (Schmalzer, 2014).

Chapter 9

9 Summary and General Discussion

In conclusion of this thesis, I report a brief summary of the studies and their most important motivations and results, followed by a general discussion about the main limitations of the paradigms I used and some suggestions for future work.

In this PhD thesis, I included a set of studies that provide new insights about the way in which haptics and vision perceive some specific spatial properties (regularities) with the final goal of gaining a better understanding about shape representation and about the concept of objectness.

In the first part, I used raised line stimuli to investigate how haptics acquires, represents and recognizes spatial information into a meaningful object. The main goal here was to try and understand whether the difficulty in recognizing raised line stimuli would lie in having to store haptic information in working memory during the slow exploration or in problems in matching the haptic percept to a stored mental image. The results suggested that externalization through simultaneous sketching aided identification and this was possibly due to reducing the burden on working memory processes and helping to guide haptic exploration.

In the second part, I used 3D planar shapes and lines to probe several cues to objectness in regularity detection tasks. In four chapters, I investigated detection of symmetry and repetition by haptics and vision. Despite the ubiquitous occurrence of these regularities in our environment, repetition has never been investigated by haptics before. Previous visual research suggested that symmetry could be a cue for the presence of one object whereas repetition could be a cue for the presence of multiple, similarly shaped, objects. In Chapter 3 I focused on this interaction to test whether the two modalities could use the same cues to perceive shapes. I also manipulated several modality-specific factors, such as *hand exploration* for haptics and *viewing perspective* for

vision. Using the same task and the same stimuli, the interaction was replicated for vision but not for haptics. This suggested that the two modalities use cues in different ways to represent shape.

A problem with this initial study into regularity detection was that it compared regularity to anti-regularity, because the stimuli had mismatched contour polarities. In Chapter 4, I overcame this issue using pairs of line stimuli (without the problem of contour polarity) and manipulating their separation as a cue to objectness. The expected interaction was found for vision but not for haptics.

Another way to overcome the regularity/anti-regularity issue was to manipulate the contour polarity of our stimuli and match it also for repetition. This was tested in Chapter 5. Here, the results replicated the effects reported by Baylis and Driver (1994, 2001) for vision but not for haptics. Generally, vision was affected more by the number of objects whereas haptics was affected more by the contour polarity and the results were still different between haptics and vision.

In Chapter 6, which used only visual stimuli, I tested whether these differences in previous results were due to the critical differences in the way in which the two modalities explored the world (local and serial for haptics versus global and parallel for vision). I forced vision to explore the stimuli in a serial way, using a moveable aperture. With vision exploring like haptics, the interaction between regularity-type and objectness was lost. In another experiment, I used the same aperture method and manipulated the complexity of the stimuli (not the number of objects). Symmetry is normally immune to stimulus complexity (because it relies on automatic, parallel processes, e.g. Richards & Hoffman, 1974) but repetition is not. However, serializing visual exploration using aperture viewing meant that symmetry lost the immunity to complexity and showed a similar pattern to repetition. Overall, the results suggest that diverse cues combine to define haptic objects, with some cues (proximity and contour polarity, i.e., the concavities and convexities along a contour) also being used by vision, but other cues being modality specific (regularity-type, line separation and whether stimulus exploration involves one rather than two hands).

Finally, in the last part I used 3D novel objects to test the role of reference frames in a symmetry detection task and to test whether the presence of symmetry versus minor asymmetries influenced performance in a preference task.

In Chapter 7, I manipulated the position of objects and the orientation of their axes to investigate which reference frame was more important for this task, body-centred or hand-centred. Haptic detection of symmetry was better for objects presented in front and aligned to the body than those explored on the side suggesting that overlapping multiple reference frames would aid haptic shape perception by minimising conflict and ambiguity in the coding of spatial relations.

Finally, in Chapter 8 I used the same 3D stimuli in a preference task. Generally, in visual studies reported in literature, symmetry is associated with aesthetic preference. Here, preference for symmetry for vision was confirmed and, for the first time, it was also found for haptics.

General Discussion

This thesis includes a wide range of studies and specific findings as summarised above. However, I feel that the main theoretical contribution of the thesis is the attempt to start understanding what it means for something to be an object for vision and for haptics. The difficulty and ambiguity in defining what is an object is rarely discussed in literature but it is surely an important issue in the field of perception. Also, as far as I am aware, this topic has never been touched by haptics before.

The converging evidence from my main set of studies investigating objectness in regularity detection (Part 2) suggests that the nature of an object differs between haptics and vision. In other words, regularity detection effects may be most informative about modality-specific differences in how stimuli are encoded and processed across vision and touch. This conclusion is consistent with the claims of Feldman (2003): "*Objects cannot be adequately defined by any simple physical property, nor even any simple perceptual property; they require a more abstract definition*" (p. 256).

Understanding the nature of objectness will involve specifying how our subjective, internal, perceptual interpretations are organised and how this

kind of organization most naturally decomposes into object-like components, rather than just focusing on how the physical world is structured. As I showed in this thesis, this may differ for haptics and vision. In accordance with Feldman (2003), an object should be specified relatively to the system processing it and relatively to the manner of its exploration. For this reason, it will require a modality specific definition. In these terms, a preliminary definition of object could be:

- A *'haptic object'* is the product of the set of spatial cues which combine to specify the final percept depending on the exploration allowed by haptics;
- A *'visual object'* is the product of the set of spatial cues which combine to specify the final percept depending on the exploration allowed by vision;
- A *'visuo-haptic object'* is the product of the differences between each haptic and visual spatial cue which can be combined to specify the final percept depending on the exploration allowed by vision and haptics.

My aim for the work within this thesis is that it can provide a preliminary framework for studying and determining which visual and haptic cues matter in the determination of objectness.

Limitations and ideas for future works

The overall aim of this work was to try to understand the nature of haptic objects relative to visual objects. Although in my studies I propose that several potential cues to objectness have been manipulated, I should reiterate, that even in vision, it has proven difficult to provide a formal definition of objectness (Feldman, 2003), whilst in haptics this topic does not appear to have been addressed at all. I do not claim that I have objectively varied objectness nor do I consider that objectness is a clear-cut, all-or-nothing attribute of stimuli. The original goal of understanding shape representation and the concept of objectness was surely quite ambitious for a single thesis. I was unable to provide sufficient empirical evidence to offer a full theoretical account of how objects are defined for haptics. My findings did, though, emphasise the importance of not just spatial cues but also the effect on coding of these cues caused by differences in the way the stimuli were explored. This is unsurprising given that this question is still unsolved even for vision. In

summary, although there is not yet a complete understanding of what it means to be a haptic object or a visual object, the work presented in this thesis should provide a solid basis from which to motivate further research to try and discover more and more about what it means to be a perceptual object.

I also wish to emphasise that in the present thesis I did not attempt to provide a complete account of haptic regularity detection. Such an account is not available for vision either, despite well over a century of research, so it would be surprising if this could be achieved for haptics at such an early stage.

Previous studies which investigated the interaction between regularity detection and objectness in vision using anti-repetition (Baylis & Driver, 1995; Bertamini et al., 1997; Bertamini, 2010; Koning & Wagemans, 2009; Lawson & Cecchetto, 2015) used a mixture of cues including closure, regularities, colour, luminance, 3D projections and stratification in depth to distinguish one-object from two-objects stimuli. Consistent with this approach, I suggest that multiple cues to objectness are extracted in different ways from perceptual inputs from our sense of touch.

An important issue for future research will be to try to understand the relative importance of these cues in determining objectness, how they are combined and how any conflicts between them are resolved. Another cue which might be worthy investigating in future researches could be rigidity, with common movement cueing for the presence of a single object.

Another interesting question could be whether or not regularity detection is also influenced by other aspects of haptic exploration which were not manipulated experimentally in the present studies. From pilot testing and informal observation, it appeared that regularity detection depends critically on aligning simultaneously in time the inputs from two matched parts of a regular stimulus. In addition, the angle of a finger relative to a contour or edge (on the left or right side or on top) may influence how that contour is perceived. Future research should probe how such changes in exploration strategies may influence the detection of regularities and the perception of objectness.

Finally, it would also be interesting to extend this research on regularity detection to blind individuals, to investigate the role of visual experience. Cattaneo and colleagues (2010, 2013) reported a series of memory studies in

which participants had to remember haptic configurations which were symmetrical or asymmetrical. There were no major differences between sighted blindfolded and late blind individuals, but these two groups differed from the early blind individuals. In particular, the orientation of the axis of symmetry was crucial for sighted and late blind individuals, but it was not important for the early blind participants. The authors suggested that any visual experience may play a crucial role in determining the spatial frame of reference used to represent shapes (Cattaneo et al., 2010, 2013). In my thesis I investigated the role of spatial frames of reference and it is important to consider whether any effects of reference frame depend on having visual experience.

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Notes

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