COMPARING THE ATTAINMENT OF OBJECT CONSTANCY IN HAPTIC AND VISUAL OBJECT RECOGNITION

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Matthew Peter Craddock

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*"touch [is] the first sense, the root and ground, as
it were, of the other senses, the one which entitles
a living thing to be called sensitive"*

~Thomas Aquinas.

"I love deadlines. I like the whooshing sound they make as they fly by."

~Douglas Adams.

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ABSTRACT

The attainment of object constancy – the ability to recognise objects across a variety of conditions that may have profound influence on perceptual input – is a topic that has been hitherto underexplored in the haptic modality, despite being a driver of a substantial body of research in visual object recognition. Recent research has found some similarities between visual and haptic object recognition and raised questions as to whether vision and haptics share common, multisensory representations. Furthermore, the potential influence of handedness in haptic object recognition had been overlooked. We tested haptic and visual object recognition on a variety of tasks, including name priming, old/new recognition, and sequential shape matching, using both familiar and unfamiliar stimuli. Haptics displayed similar orientation-sensitivity to visual object recognition, but is also relatively insensitive to haptic-specific manipulations such as changes of exploration hand or the influence of handeness. Haptics and vision also displayed similar sensitivity to changes of object size in both unimodal and crossmodal testing. These findings strongly support an account of object recognition in which vision and haptics share representations that are sensitive to both orientation and size. Thus, these representations are perceptual in nature rather than much more abstract representations of shape or semantic labels such as names. Therefore, the findings in this thesis support a multisensory account of object recognition and attainment of object constancy.

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CHAPTER 1| Introduction

1.1 The problem of haptic object recognition

Object recognition is a task that is fundamental to our lives. Somehow, we rapidly and efficiently process the complex and often ambiguous information we receive from our senses to experience the world as populated by other objects, both animate and inanimate. Intuitively, we think of object recognition as a visual process, something we do while looking around, without necessarily even thinking about it; yet we are also capable of recognising an object by touch when, for example, rummaging in a bag to find our keys. This use of touch as an active, exploratory sense has been termed *haptics*, and is distinct from (although clearly related to) passive, *tactile* touch. Haptic object recognition was long considered a poor relative of visual object recognition, since people's ability to recognise 2D raised-line depictions of common objects by touch alone is quite poor (Lederman, Klatzky, Chataway, & Summers, 1990; Loomis, Klatzky, & Lederman, 1991; Magee & Kennedy, 1980). However, haptic recognition of real, familiar objects is – perhaps surprisingly – both fast and accurate (Klatzky, Lederman, & Metzger, 1985; Craddock & Lawson, 2008).

Early models of haptic object recognition (Lederman & Klatzky, 1987; Lederman et al., 1990) were largely descriptive, providing only outlines of the steps involved in haptic recognition with little clear specification of how those steps were achieved. In contrast, more clearly specified models of visual recognition, such as Biederman's recognition-by-components model (1987), were being developed that would be used to explain a wide range of research findings. Subsequent models of visual object recognition (e.g. Riesenhuber & Poggio, 1999) developed on these foundations, drawing on behavioural and neuropsychological evidence and computational modelling, and advances in neuroimaging have allowed in-depth study of the neural process involved in visual object recognition (e.g., Bar et al., 2006; Vuilleumier, Henson, Driver, & Dolan, 2002). To date, visual object recognition remains more comprehensively explored and modelled than haptic object recognition.

The present thesis adapts one of the key problems in modelling visual object recognition to the haptic modality: the ability to recognise objects across a wide variety of conditions that disruptively transform perceptual input, or *object constancy*. Thus, for example, the retinal image projected by an object may differ when that object is seen from different viewpoints. Investigation of this problem drove and continues to drive visual object recognition research. It is only recently, however, that research has demonstrated that haptic object recognition encounters many similar difficulties in attaining object constancy to those encountered by vision. For example, haptics and vision both suffer costs of generalizing recognition across different viewpoints or orientations (e.g. Craddock & Lawson, 2008; Lacey, Peters, & Sathian, 2007; Lawson, 1999, 2009; Newell, Ernst, Tjan, & Bülthoff, 2001), and across objects of different sizes (Craddock & Lawson, 2009a, 2009b). Thus, behavioural evidence suggests at least superficial similarity between the two modalities. A fundamental question, therefore, is whether these similarities between vision and haptics arise from the use of the same processes and representations.

First, I will examine the early models of haptic object recognition as proposed by Klatzky, Lederman and colleagues during late 1980s and early 1990s. Second, I will examine the behavioural evidence regarding haptic information processing. Third, I will outline the physiological, neural processes involved in the haptic processing of shape. Fourth, I will examine how evidence from neuroimaging suggests substantial overlap between the neural areas involved in visual and haptic object recognition, and then some of the related behavioural evidence. Fifth, I will outline existing models of visual object recognition. Finally, I will introduce the experiments which constitute the bulk of this thesis.

1.2 Early models of haptic object recognition

Early research into haptic object recognition indicated that it was poor relative to visual object recognition. For example, evidence from experiments on visual and haptic sensory integration indicated that vision dominated haptics in the perception of 3D shape (Rock & Victor, 1964). Bryant and Raz (1975) found that tactile discrimination of 3D novel shapes was more difficult than visual discrimination of the same shapes. Furthermore, Magee and Kennedy (1980) examined the haptic identification of raised line drawings of familiar objects by sighted, blindfolded participants, and found that only 17% of drawings were recognised when participants were allowed to freely explore them with their hands. Thus, there seemed to be compelling evidence that vision generally dominated haptic recognition, outclassing it in recognition of both 3D objects and 2D depictions of objects.

However, Klatzky et al. (1985) demonstrated that haptic object recognition can be both fast and accurate. Participants identified 100 familiar objects using only haptic touch; naming accuracy was almost perfect, and almost all responses were made in under 5 seconds. Klatzky et al. thus demonstrated that haptic object recognition was far more effective than had previously been realized, arguing that previous experiments used stimuli that lacked many of the cues to object identity that haptics uses most effectively: Participants reported that they typically used object characteristics such as global shape, texture, and compliance to facilitate identification. Such cues are hard to simulate using 2D raised line drawings of familiar objects, and were often uninformative for novel objects.

Klatzky and Lederman (1987) argued that a flawed model of haptic object recognition they called *image-mediation* had been implicit in the interpretation of the research that had preceded their work. According to the *image-mediation* model, the sensory input received by the cutaneous and kinaesthetic haptic sensors is translated into a visual image, and is thereafter processed as if it had originated from visual sensors. Thus, from an early stage, the haptic and visual systems share common processes which, ultimately, are characterised as visual rather than haptic or multisensory. Haptics itself has no processing of its own by which it can recognise an object. In contrast, they proposed the *direct-apprehension* model, in which haptics constitutes a separate perceptual system from vision, and has its own processing and physiological apparatus. On this account, vision and haptics only share later processes. The two modalities can share a common representation of objects, but also maintain visual and haptic specific representations. Note that these two models are not mutually exclusive, and may describe the performance of the haptic system under different conditions.

Nevertheless, both *image-mediation* and *direct-apprehension* models lacked specification. Both models posit shared processes and representations between haptics and vision, but say little about which processes and the qualities of those representations. Both make somewhat contrasting predictions about haptic object recognition. According to image-mediation, haptics has no specific processes and representations of its own; all object recognition is dealt with by the visual system. If this were correct, then haptic object recognition should display considerable similarity to visual object recognition, differing only as a direct result of the constraints of the haptic perceptual system. In contrast, direct-apprehension argues that only later processes and representations are shared between vision and haptics. This suggests that the performance of the two modalities might differ considerably in some circumstances.

Several important questions are raised by these models. Firstly, what are the physiological and neurological systems which underpin haptic perception, and how are these systems marshalled in the service of object recognition? Do these systems indicate that haptics has its own route to object recognition or that it delegates all responsibility to the visual system, and how closely do they mirror either model? Secondly, at what stage do vision and haptics begin to share processes and representations? What are the qualities of the representations that are shared between vision and haptics? If vision and haptics also have distinct representations, how do these differ from those that are shared? Finally, how does haptic object recognition cope with everyday variation in object properties? Does it suffer similar costs to those incurred by vision when generalizing across different object properties?

1.3 Haptic information acquisition

Klatzky and Lederman (1987) argued that a set of relatively stereotyped patterns of hand movements called *exploratory procedures* (EPs) were a key early stage in haptic object recognition. Lederman and Klatzky (1987) examined the hand movements of participants who were instructed to use particular characteristics to haptically match objects. For example, participants were sometimes told to match two objects on the basis of texture, weight, or temperature. Participants tended to use particular EPs to assess specific qualities of the objects. Examples of EPs include *contour following*, in which the hands follow the edges of object to establish its precise shape; *enclosure*, in which the hands mould to the surfaces and edges of the object to establish its global shape and volume; and *lateral motion*, in which the hands move along the surface of the object to sense its texture. Thus, when matching using these properties, participants tended to use these EPs. Klatzky and Lederman (1987) argued that these EPs allowed the haptic system to supplement the information derived from the sensory apparatus of the skin with information derived from our motor system.

Lederman et al. (1990) argued that the superiority of haptic recognition of familiar, real 3D objects (Klatzky et al., 1985) to haptic recognition of 2D depictions of those objects (e.g. Klatzky, Loomis, Lederman, Wake, & Fujita, 1993) is because *direct-apprehension* can be used with real 3D objects. Cues present with real, 3D stimuli (e.g. weight, texture) are absent from 2D depictions, and real objects allow the use of the natural EPs that the haptic system typically employs (Lederman & Klatzky, 1987). Lederman et al. (1990) tested haptic recognition of 2D raised line pictures of common objects, and found that performance was extremely poor and slow in comparison to recognition of real familiar objects (Klatzky et al., 1985), replicating earlier research (e.g. Magee & Kennedy, 1980). They argued that the haptic recognition of 2D raised-line pictures was poor because it forced the haptic system to use *image-mediation*, which necessitates the integration of spatially and temporally separated details and translation of this input into a visual image. Performance on individual objects correlated strongly with ratings of the imageability of those objects, and participants who reported strong visual imagery also performed better than those who did not, supporting the involvement of a haptic-to-visual translation process.

However, an additional factor in making recognition of 2D raised-line drawings difficult is that the field-of-view of the fingers is relatively limited in comparison to that of the eyes. Loomis et al. (1991) forced the visual system to operate under similar conditions as those of the haptic system by limiting field-of-view and degrading image resolution. Vision and touch performed similarly poorly when recognising 2D drawings under comparable conditions. This suggests that the difficulty of integrating small amounts of local information into a coherent global shape over extended periods of time, which places heavy demands on working memory, may be a primary cause of poor haptic recognition of 2D raised-line drawings, as opposed to the limitations of haptic perception per se.

Nevertheless, complete recovery of 3D structure is not necessary for haptic object recognition. Klatzky and Lederman (1995) showed that haptic recognition of familiar objects could still be achieved when exploration was severely spatially and temporally restricted. Participants were guided to make a brief contact of an object with their fingertips at a point on the object that should be particularly diagnostic of its identity. This point either gave key information about an object's texture (e.g. the rough side of a piece of sandpaper) or about its shape (e.g. the pouring lip of a jug). Although performance was poor relative to recognition with unrestricted exploration, it was still better than was expected by chance. Thus, although the normal use of EPs was heavily restricted, local textural and shape information could still be recovered and was sufficient to provide at least some level of object recognition.

Klatzky et al. (1993) had participants identify objects haptically while wearing a glove which attenuated material object cues. The glove either allowed participants to examine the objects freely or prevented finger flexion, allowing exploration with only a single outstretched finger or five outstretched fingers. Thus, normal exploratory procedures were limited: for example, enclosure was impossible when finger flexion was prevented. Although performance was fastest and most accurate with free exploration, haptic recognition of real 3D objects was far superior to recognition of 2D depictions of those objects even when finger flexion was prevented. Furthermore, when the fingertips of the gloves were removed to allow access to material cues, only a minimal improvement in performance was observed. These results suggest both that haptics relies primarily on structural rather than material information about objects to recognise them and that these structural properties are recoverable even when EPs are restricted.

Ballesteros, Reales, and Manga (1999) also examined the contribution of material cues to haptic recognition of familiar objects. Participants first haptically judged objects on a variety of material properties such as texture or temperature. They then named the objects or performed an old/new recognition task while either gloved or ungloved. Naming accuracy was almost perfect in both gloved and ungloved conditions, although naming was faster when ungloved as opposed to gloved. Recognition memory was also very accurate, but was impaired when wearing gloves compared to without (88% versus 94% respectively). Man-made objects were also recognised significantly more accurately than natural objects (95% versus 87%). Notably, the impairment due to wearing gloves was greater for natural objects than for man-made objects. Both the accuracy and speed declines when wearing gloves were consistent with Klatzky et al. (1993), as was the greater contribution of material cues in the hardest condition (recognition of natural objects). Again, these results suggest that the recovery of 3D structure is key to haptic object recognition; material cues support recognition but are not critical to it.

1.4 An introduction to the physiology of the haptic modality

The haptic modality differs fundamentally from our other sensory modalities in that it interacts with external stimuli directly. For example, if we wish to see more than one view of an object, then we must move the object, move ourselves, or wait for the object to be moved or move itself. We can effect none of these by the use of our eyes alone. However, we can pick up an object, feeling it from multiple sides simultaneously, and move our hands in a variety of ways to examine its properties (Lederman & Klatzky, 1990). Although haptic touch is considered a unified, single modality, it is the combination of two distinct sub-modalities, the *kinaesthetic* and the *cutaneous*, which makes haptics unique.

Our muscles, tendons, and joints contain populations of mechanoreceptors providing kinaesthetic information. These mechanoreceptors, often termed proprioceptors, provide information about the movement and position of our limbs in space. Thus, our kinaesthetic sense provides us with a sense of movement through space based on internally-generated feedback. In contrast, cutaneous receptors are distributed throughout the skin and provide sensory input from interaction with our external environment. It is those of the hand that are directly relevant to the present work. Embedded in the glabrous (hairless) skin which constitutes the palm of the hand are four different populations of mechanoreceptor, characterized by the relative size (small versus large) of their receptive fields and the relative speed (slow versus fast) with which they adapt to skin deformation. These mechanoreceptors are each maximally sensitive to different stimulus features and, thus, serve different functions. For example, fast-adapting mechanoreceptors are maximally sensitive to rapid changes in skin deformation such as those caused by vibration, whereas slow-adapting mechanoreceptors are maximally sensitive to sustained pressure and very low frequency changes in skin deformation (see Lederman & Klatzky, 2009, for an overview). In addition to these four populations of mechanoreceptors, there are also two populations of thermoreceptors which sense absolute and relative changes in temperature, mediating the perception of warmth and cold. Thus, the receptors employed by haptics are more extensive and more distributed than those of any of our other sensory modalities (Haggard, 2006).

Sensory input from cutaneous and kinaesthetic peripheral receptors projects to the brain through the medulla via the dorsal column in the spinal cord. From the medulla, this input is projected to the thalamus, and from the thalamus to the somatosensory cortices. The first point of entry for sensory input into the cortex is somatosensory area SI, located around the postcentral gyrus. From this point, somatosensory and haptic processing seems to follow similar hierarchical and functional principles of organization to other sensory modalities, and particularly to vision. SI is subdivided into four anatomically and functionally distinct areas: Brodmann areas 1, 2, 3a, and 3b. Each of these areas contains a somatotopic map of the contralateral side of the body (Chen, Friedman, & Roe, 2003). The receptive fields of adjacent neurons typically overlap: adjacent neurons respond to adjacent receptors in the skin or muscles. This is similar to the retinotopic mapping observed in primary visual cortex (e.g. Engel, Glover, & Wandell, 1997).

Areas 3a and 3b are analogous to primary visual cortex (V1). Neurons in these areas have very small receptive fields which respond on an almost one-to-one receptor-to-neuron basis (Phillips, Johnson, & Hsiao, 1988). Areas 1 and 2 receive inputs from areas 3a and 3b, as well as directly from the thalamus. Neurons in areas 1 and 2 have larger receptive fields than neurons in areas 3a and 3b, responding to more complex patterns of sensory input, suggesting that they occupy a higher level of a processing hierarchy than areas 3a and 3b.

Areas 3b and 1 preferentially receive input from the cutaneous receptors of the skin, whereas areas 3a and 2 instead receive inputs primarily from proprioceptors embedded in the muscles and joints. Accordingly, neurons in these areas respond to different types of sensory input. Specifically, neurons in area 1 respond preferentially to surface features such as roughness or texture (Hsiao, Johnson, & Twombly, 1993; Randolph & Semmes, 1974), whereas neurons in area 2 are sensitive to differences in shape primitives, such as edges or curvature (Iwamura & Tanaka, 1978; Randolph & Semmes, 1974). In primates, removal of areas 1 and 2 impairs performance on texture and shape discrimination tasks respectively (Randolph & Semmes, 1974).

A further response characteristic of early somatosensory processing is sensitivity to orientation. Bensmaia, Denchev, Dammann, Craig, and Hsiao (2008) examined the responses of neurons in areas 3b and 1 in macaque monkeys to bars and edges scanned across the skin of the fingers. Many neurons displayed orientation-sensitive tuning, responding maximally to bars or edges in particular orientations. Thus, although lesions to area 1 do not normally seriously impair form discrimination (Randolph & Semmes, 1974), it nevertheless is involved in shape processing and the extraction of edges and edge orientation. This orientation-sensitive neuronal tuning is similar to the well-documented orientation-sensitive tuning of neurons in primary visual cortex (e.g. Hubel & Wiesel, 1962), suggesting that even at very early stages of processing, both the visual and haptic modalities process some shape primitives in a similar way.

Beyond early somatosensory processing, SI projects to area SII, located in the posterior parietal and insular cortex. Neurons in these areas have larger receptive fields than those in SI, responding to more complex stimuli, and thus may represent yet higher stages of processing than SI. SII – also called the somatosensory association cortex – has multiple fields of neurons that respond differentially to cutaneous and kinaesthetic inputs (Fitzgerald, Lane, Thakur, & Hsiao, 2004). Neurons in SII have large and often bilateral receptive fields (Iwamura, 2000). Whereas neurons in SI typically have receptive fields which lie within a single digit of the hand, many neurons in SII have receptive fields which span multiple digits (Fitzgerald et al., 2004). Thus, SII may be critical for the integration of different types of information derived from multiple locations. Using fMRI in human subjects, Reed, Shoham, & Halgren (2004) found that SII was active during haptic object recognition. Furthermore, lesions to SII can severely impair haptic object recognition (Reed & Caselli, 1994; Bohlhalter, Fretz, & Weder, 2002).

Yau, Pasupathy, Fitzgerald, Hsiao, and Connor (2009) compared neuronal shape selectivity in areas V4 and SII in macaques. These two areas occupy intermediate stages in the hierarchy of shape processing in the visual and haptic systems respectively. Stimuli were fragments of object contours either flashed on a computer screen or presented as embossed ridges indented into a finger pad. These 2D fragments were either angles or circular arcs, and each was presented in eight different orientations. Neurons in both V4 and SII showed comparable sensitivity to the direction in which these angles and curves pointed. Thus, these higher-order areas respond to more complex shapes than lower-order, primary visual (V1) and somatosensory (SI) cortices, both of which are tuned to recover local orientation (e.g. Hubel & Weisel, 1968; Bensmaia et al., 2008). This similarity may be an example of convergent evolution: two different sensory modalities arriving at the same solution to the same information-processing problem. Alternatively, it may have arisen to facilitate crossmodal transfer of object information, and thus aid recognition across modalities.

Although SII may be a critical area for recognition of objects by touch, it is not an endpoint for the recognition of objects. Thus far, I have examined only areas specific to haptic processing of shape, describing a pathway which, as it proceeds from primary somatosensory cortex to higher-order somatosensory areas, responds to increasingly complex configurations of stimuli and may subserve haptic object recognition. This haptic pathway shows hierarchical and functional organization similar to the visual system and seems to encode low-level shape in the same way; thus, it is also possible that they encode higher-level representations of shape in the same way, and may use the same high-level representations of shape when recognising objects. This in turn implies that there will be both neural and behavioural overlap between visual and haptic object processing.

1.5 Neural overlap between visual and haptic object recognition

SII is not the only destination for projections from SI. SI areas 1 and 2 also project to Brodmann areas 5 and 7, located along the anterior intraparietal sulcus (aIPS). The aIPS shows selectivity for overall object shape as opposed to selectivity for particular shape primitives, showing greater neural activation during tasks involving length or shape discriminations as opposed to texture discriminations (Bodegård, Geyer, Grefkes, Zilles, & Roland, 2001), and has also been found to be active during haptic object recognition (Amedi, Malach, Hendler, Peled, & Zohary, 2001). However, aIPS is not a purely haptic area: it also receives inputs from the visual system (e.g. Zhang, Weisser, Stilla, Prather, & Sathian, 2004). Furthermore, its activation during haptic object recognition tasks does not necessitate that the aIPS is directly involved in recognition. aIPS is normally considered part of the dorsal stream in the visual system – the "where" pathway (Goodale and Milner, 1992; Milner and Goodale, 2008), and it may have a role in processing shape information for visually directed reaching and grasping movements (James, Culham, Humphrey, Milner, & Goodale, 2003).

Milner and Goodale (2008) argue that the dorsal stream, which proceeds from early visual cortex to higher-order cortical areas in the parietal lobe, predominantly serves action.

Thus, representations of objects in dorsal areas may be transient representations of the metric qualities of perceived objects, suitable only for interaction with those objects. In contrast, object recognition is subserved by a distinct "what" pathway – the ventral stream. The ventral stream is based in the temporal lobe, and contains several functionally distinct areas which may be specialized for the recognition of particular categories of object (e.g. the fusiform face area, specialized for face recognition, see Kanwisher, McDermott, & Chun, 1997).

A key area in this stream is the lateral occipital complex (LOC). LOC is particularly implicated in the processing of visual shape (Grill-Spector, Kourtzi, & Kanwisher, 2001; Kourtzi, Erb, Grodd, & Bülthoff, 2003; Zhang et al. 2004), showing activation in response to photographs (Malach et al., 1995) or line drawings (Kanwisher, Chun, McDermott, & Ledden, 1996) of either familiar or unfamiliar objects but not during viewing of images which do not contain a clear shape. Although the LOC was initially considered to be exclusively dedicated to visual processing, there is now a considerable body of neuroimaging evidence demonstrating that it is also involved in haptic processing of 3D shape (Amedi, Jacobson, Hendler, Malach, & Zohary, 2002; Amedi, von Kriegstein, van Atteveldt, Beauchamp, & Naumer, 2005; Amedi et al. 2001; Deibert, Kraut, Kremen, & Hart, 1999; James, Humphrey, Gati, Servos, et al., 2002; James, Kim, & Fisher, 2007; Miquée et al., 2008; Sathian & Lacey, 2007; Zhang et al. 2004).

Both image-mediation and direct-apprehension would predict some sharing of processes and representations between vision and haptics, and thus mutual activation of LOC fits into both models. However, they differ in how they would explain this mutual activation. Image-mediation suggests that it should be purely due to visual imagery. If this account were correct, then similar patterns of brain activity should be observed during visual imagery tasks and haptic object recognition. Furthermore, there should be little indication of a haptic-specific pathway for object recognition. In contrast, the direct-apprehension account would suggest that there may be pathways for haptic object recognition without reference to vision, and that activity during haptic object recognition should be comparable to activity during visual object recognition per se rather than activity during the use of visual imagery.

There is evidence of haptic-specific pathways to object recognition, but greater evidence that visual and haptic recognition converge on the same neural areas. Furthermore, the role of visual imagery in this process appears to be somewhat limited. Reed et al. (2004) studied brain activity during haptic object recognition using fMRI. Participants covertly named real, familiar objects (varying from a whistle to a tennis ball to a book) or palpated nonsense objects made from balsa wood. The nonsense objects served as sensorimotor controls; by subtracting activation when palpating nonsense objects from activation when palpating familiar objects, activity from primary motor and somatosensory areas could be accounted for. Reed et al. (2004) found that some areas of somatosensory association cortex that were only activated by palpation of real, familiar objects, indicating the presence of a pathway specific to haptic object recognition. Additionally, activity was also observed in LOC.

James, Humphrey, Gati, Servos, Menon et al. (2002) examined cross-modal priming for novel, 3D objects using fMRI. Participants studied complex 3-D novel clay objects either visually or haptically. During scanning, participants were shown greyscale photographs of the studied objects. They were also shown photographs of and haptically explored similar but unprimed objects, which produced significant activation in several brain regions when explored haptically and visually, with overlapping activation in the middle occipital (MO) area. Primed objects produced greater activation in the MO area and in the LOC.

Amedi et al. (2001) showed that both haptic and visual object exploration activate the LOC, which showed a clear preference for geometric objects with less activation during examination of textures in both modalities. No activation was observed in LOC during naming or motor control conditions, suggesting that the activation observed during haptic object recognition was not due to linguistic or motor functions. Furthermore, in a visual imagery condition, activation was low in comparison to activation during haptic exploration of objects, suggesting that visual imagery has only a limited role in translating haptic input. Additionally, the LOC is not activated by auditory stimuli diagnostic of object identity, such as the sound of a car engine (Amedi et al. 2002). These results suggest that at least some part of the LOC is dedicated to the integration of shape information derived from both vision and touch, leading Amedi et al. (2002) to designate the area of overlap between visual and haptic recognition in LOC as the lateral-occipital tactile-visual (LOtv) area. Furthermore, Amedi et al. (2007) found that shape information conveyed by a visual-to-auditory sensory substitution device, which converts visual shape information into an auditory stream using a variety of auditory parameters to represent different aspects of the visual image, also activates LOtv. They argued that since audition contributes little to the perception of 3D shape, unlike vision and touch, the LOtv is probably involved directly in the recovery of 3D shape.

There is some evidence that the LOC is involved in visual imagery. Newman, Klatzky, Lederman, and Just (2005) instructed participants undergoing fMRI scanning to imagine material and geometric features of objects. Participants were given the names of objects. They either mentally evaluated each object along a material (for example, roughness or hardness) or a geometric dimension (for example, size or shape), or were given a material name along with the object name and asked to evaluate how relevant that material property was to the object in question. Although there were some additional regions active which differed according when imaging material (evoking activity in the inferior extrastriate region) versus geometric properties (evoking activity in the intraparietal sulcus), the LOC was consistently activated irrespective of the feature type being queried. LOC activation was maximal for processing of shape and roughness, which may both rely heavily on shape extraction. Nevertheless, the activity observed may not accurately represent the processes involved in the actual perception of the material or geometric properties of objects.

Zhang, et al. (2004) also found that visual imagery contribute to some of the activity observed in LOC during haptic object recognition: participants' reports of vividness of mental imagery correlated with LOC activation in the right hemisphere though not the left. However, not all of the activation could be explained by visual imagery.

Pietrini et al. (2004) used fMRI to examine neural responses during visual and haptic recognition of faces and manmade objects in sighted participants and during haptic recognition in blind participants. They found regions of visual and haptic overlap in the LOC, similar to that observed by Amedi et al. (2001, 2002), and in inferotemporal (IT) cortex. Activity in IT appears in category-related patterns; for example, the pattern of activation observed is different for faces than for man-made objects. For sighted participants, these patterns correlated across modalities for man-made objects though not for faces. This suggests that, for man-made objects at least, the same representations are accessed whether objects are identified haptically or visually. That the patterns differed for faces suggests that the two modalities may use different representations of faces, and participants reported that they used quite different strategies for recognising faces haptically as opposed to visually. Blind participants also showed comparable patterns of category-selectivity for man-made objects. Thus, this activity was not due solely to visual imagery, and visual experience was not necessary for the development of representations in these areas. This is consistent with Amedi et al.'s suggestions that vision and haptics share representations, and that involvement of visual areas in haptic object processing cannot be explained by the use of visual imagery alone.

Deshpande, Hu, Stilla, and Sathian (2008) examined effective connectivity during haptic recognition to test whether haptic recruitment of visual cortex was driven by top-down inputs, thus implicating a primary role for visual imagery, or bottom-up inputs from somatosensory cortices, which would imply that haptics recruits a multisensory representation housed in visual cortex. Effective connectivity is a method of estimating the direction and strength of connections between the brain regions active during a task. This analysis revealed that the post-central sulcus – part of the primary somatosensory cortices – was a key driver of activity in LOC and MOC during haptic perception, strongly favouring the hypothesis that somatosensory cortex feeds directly into visual cortex without need for translation into a visual image.

Subsequent research has suggested that imagery may be more involved in the haptic perception of familiar objects than unfamiliar objects. The brain networks involved in visual imagery tasks overlapped more with those involved in the haptic recognition of familiar objects (Deshpande, Hu, Lacey, Stilla, & Sathian, 2010; Lacey, Flueckiger, Stilla, Lava, & Sathian, 2010).

Although the evidence summarized above shows the LOC is active during both visual and haptic object recognition, one problem is that the spatial resolution of fMRI is generally too low to distinguish between neural populations within individual voxels. Each voxel in an fMRI scan can contain millions of individual neurons. Thus, it is possible that the common activation observed in LOC is not multisensory; instead, comparable populations of visual- and haptic-specific neurons occupy the voxels which contain the LOC. Tal and Amedi (2009) circumvented this problem using adaptation. Adaptation relies on the repetition-suppression effect (Grill-Spector et al., 1999) - declining activation with repeated exposure to a stimulus. Thus, in an object-selective region such as LOC if one population of neurons is tuned to respond to any object then repeated presentations of any objects will cause decline in activation. If, however, the LOC contains a mixture of several neuronal populations, each tuned to particular objects, then the fMRI signal would only decline as long as the same object was repeated; it would rebound when a new object appeared. This effect has been used to study the response characteristics of neurons in the LOC to a range of manipulations of visual stimuli (e.g. Grill-Spector et al., 1999; James, Humphrey, Gati, Menon, & Goodale, 2002; Vuilleumier et al., 2002).

Tal and Amedi (2009) used this technique to test whether LOC would display an adaptation effect following crossmodal transfer. If LOC contained separate populations of visual and haptic neurons then adaptation would not occur when a change of modality of presentation occurred for repeated objects. On the other hand, if LOC used a bimodal, multisensory code to represent objects, then adaptation effects should still occur when an object was repeated in different modalities. LOC continued to show an adaptation effect under crossmodal conditions, suggesting that processing there is truly bimodal.

Lacey, Tal, Amedi, and Sathian (2009) proposed a model of multisensory object recognition encompassing the above findings. In their model, the LOtv contains a multisensory object representation which can be flexibly accessed through both bottom-up, sensory input and top-down, image driven output. This access can be had independent of the input modality. This model separates visual imagery into *object-* and *spatial-* imagery. Object imagery is closer to the canonical notion of a visual image, being a mental "picture" and deal with a literal representation of the appearance of an object, representing its shape and surface characteristics such as texture and colour. Spatial imagery instead represents objects as more abstract, schematic representations of object components and their spatial relationship to one another. When exploring unfamiliar objects, haptics relies largely on a combination of spatial imagery driven by top-down pathways from prefrontal areas and bottom-up somatosensory input, whereas when exploring familiar objects, bottom-up haptic input is supplemented by object imagery as well as spatial imagery and somatosensory input.

There is thus strong, compelling evidence that visual and haptic object recognition are underpinned by the same neural structures and networks, and that the two share representations of shape which are best characterised as multisensory. However, neuroimaging and neurophysiology can only take us so far. The evidence discussed thus far tells us little about the behavioural implications of this sharing of representations between vision and haptics. Note, also, that the processes described are for the recognition of 3D objects. Given that the two modalities feed into the same neural areas, does this imply that haptically and visually acquired representations are equivalent? What format do these representations take? Are they abstract representations of structure, as proposed by some models of visual object recognition (Biederman, 1987), or are they more perceptually based?

1.6 Crossmodal transfer and perceptual equivalence between vision and haptics

Cooke, Jäkel, Wallraven and Bülthoff (2007) conducted a multidimensional scaling analysis of visual and haptic ratings of similarity between pairs of novel objects, and found that the ratings from both modalities were influenced by shape and texture. Vision weighted shape as more important than texture for determining similarity, whereas haptics weighted shape and texture as equally important. Nevertheless, the same perceptual map could account for the pattern of ratings from both modalities, consistent with the hypothesis that the two modalities share common representations.

Lakatos and Marks (1999) examined the weighting of local and global object features by the haptic system in comparison to the visual system. Participants rated the similarity of pairs of novel objects that varied parametrically in local and global shape. Objects with comparable global shape but differing local features were rated as less similar when compared haptically than when compared visually, suggesting that haptics weights local features more heavily than vision. Subsequently, participants performed haptic comparisons when wearing thick gloves, which discouraged the use of contour-following exploratory procedures, or splinted gloves, which discouraged the use of enclosure. These EPs had previously been associated with the extraction of local and global features respectively (Klatzky, Lederman & Reed, 1987). Ratings of similarity were comparable in both gloved conditions, suggesting that the links between specific EPs and specific types of features may not be as distinct as previously suggested. While some EPs may perceive certain features optimally, they are not necessary to perceive those features. In a final experiment, participants were given restricted time to explore the objects haptically. Objects with similar global shape but distinctive local features were rated as more dissimilar when exploration time was short, and more similar as longer exploration was allowed. Thus, the haptic system may weight local features more heavily than global shape initially, forming a global representation through successive explorations of local features.

There is compelling behavioural evidence for efficient sharing of information about objects between vision and haptics. Reales and Ballesteros (1999) found that cross-modal priming between vision and haptics is excellent for familiar objects. Participants studied objects visually or haptically. Level of processing was varied at study by having participants either generate a sentence including each object's name (*deep* encoding) or rate each object's volume (*shallow* encoding). At test, participants named each object when it was presented either to the same modality as at study or to the other modality. There was no speed or accuracy cost associated with encoding condition or with a change in modality between study and test, indicating complete cross-modal transfer of priming.

Effects of level of processing are commonly used to distinguish explicit from implicit memory. Typically, manipulations of levels of processing affect explicit but not implicit measures of memory (e.g., Meier & Perrig, 2000). Reales and Ballesteros (1999) argued that the absence of a level of processing effect in their study indicated that both visual and haptic priming of naming was implicit, underpinned by abstract, pre-semantic, structural descriptions of object shape that were not modality-specific.

Easton, Greene, and Srinivas (1997) also compared implicit and explicit measures of recognition of 3D familiar objects. Their participants named visually or haptically presented objects at study. At test, they either named the objects again – an implicit priming task – or were asked to state which object they had been given before – an old/new, explicit recognition memory task. Both tasks were conducted either visually or haptically. Explicit memory showed modality-specificity: haptically studied objects were best recognised haptically, and visually studied objects were best recognised visually. Neither the haptic nor visual implicit priming tasks showed a significant effect of study modality, but comparisons across the two suggested a marginal within-modal advantage. Both the explicit and implicit task results suggest that cross-modal transfer between vision and haptics may not be complete, contrary to Reales and Ballesteros' (1999) findings.

Implicit measures are often less reliable than explicit measures (Buchner & Brandt, 2003; Buchner & Wippich, 2000; Meier & Perrig, 2000). The reliability of a measure influences statistical power: less reliable measures have less power to find an effect. Thus, the lack of both modality-specific priming and a level of processing effect reported by Reales and Ballesteros (1999) may have been due to low statistical power rather than reflecting the operation of distinct memory systems.

Other evidence suggests that cross-modal priming may depend upon a network of representations spanning verbal, visual, and haptic codes of representation. Lacey and Campbell (2006) found that cross-modal recognition of familiar objects was unaffected by visual, verbal, or haptic interference either at study or at test. Since no one method of interference selectively influenced performance to a greater degree than any other, they suggested that object representations can be both formed and retrieved using a multitude of codes. However, performance on familiar objects was close to ceiling, making it difficult to assess the relative contributions of each of these codes. Recognition of unfamiliar objects, on the other hand, was impaired by verbal and visual interference at study. Bushnell and Baxt (1999) examined children's haptic and crossmodal recognition of familiar and unfamiliar objects. They found that unimodal visual and haptic recognition and crossmodal recognition were excellent for familiar objects. However, they found that crossmodal recognition was poorer for unfamiliar objects than for familiar objects.

The crossmodal results thus imply that visual, haptic and crossmodal representations may not be fully equivalent. Supporting this, Phillips, Egan, and Berry (2009) found haptics became less capable of discriminating between stimuli as they became more complex, whereas vision was able to discriminate the stimuli reliably across the full range of complexity. Nevertheless, it seems clear from both behavioural and neuroimaging evidence that there is much, if not complete, sharing of representations and processes between vision and touch. As such, it is necessary to consider what existing models of visual object recognition might lead us to predict would be likely behavioural phenomena in haptic object recognition.

1.7 Models of visual object recognition

The earliest tranche of the modern era of visual object recognition belongs to the *structural description* models. The progenitor of these was that of Marr & Nishihara (1978). They proposed that object recognition was accomplished by forming part-based structural descriptions of objects based on 3D volumes, representing individual object parts, and the spatial relations between those volumes. It was they, also, who highlighted a particular problem that was to become a topic of much debate and research in the field: viewpoint. They argued that it was more efficient to represent objects using an object-centred co-ordinate space than a viewer-centred co-ordinate space. For the former, a single representation could represent an object from many different angles, whereas the latter would reflect the specific viewpoint from which the object was previously seen, and thus would not aid recognition from other viewpoints. Marr & Nishihara's model was an important landmark; however, it provided mainly a theoretical framework, and lacked empirical backing.

Biederman's recognition-by-components theory (1987) was a considerable development of the *structural description* theory. Biederman gave a much fuller account of the sequence of stages which allow object recognition under such a model. First, edges are abstracted from visual input to the retina; differences in surface characteristics such as luminance, texture, or colour are effectively discarded here. This stage provides what Biederman describes as a "line drawing description" of the object. Two subsequent, parallel processes determine non-accidental image properties, such as symmetrical edges, and parse the image into individual regions, typically using concavities implied by the configuration of the edges. These two processes result in the segmentation of the image into approximations of individual shape components: *geons*. Geons are simple, volumetric primitives such as cylinders or spheres. The next stage is to describe the spatial relationship between these geons. Different arrangements of the same geons can describe different objects, and thus only a small set of geons is necessary to form a practically infinite number of objects. the resulting structural description to a stored description in order to identify the object. For example, a cylinder with an arc connected to its side may be a description of a mug; the same cylinder with an arc connected to its top may instead be a description of a bucket. In this account, surface characteristics such as colour or texture play only a secondary role in object recognition.

Biederman argued that this model allowed for orientation-invariance under most circumstances: the same object would produce a description of the same parts in the same spatial relations under most condition other than unusual viewing orientations when parts are occluded from sight. Indeed, Biederman and Gerhardstein (1993) subsequently provided evidence that priming of object naming was often unaffected by changes of orientation. Biederman's model was never intended to account for object recognition in general; for example, it did not attempt to describe how members of a given class of object were differentiated from one another (for example, different breeds of dog). Nevertheless, it was a promising step-forward which allowed detailed predictions to be made.

However, subsequent evidence suggested that, in most circumstances, visual object recognition is sensitive to orientation and orientation changes (e.g. Lawson, 1999). Tarr and Cheng (2003) suggest that orientation-invariance is the exception rather than the rule, and can be accounted for by models which propose the storing of multiple views of objects. Poggio and Edelman (1990) devised a view-based model in which matching of novel views of objects was achieved by a process of interpolation between known views. Views equidistant between two known views are recognised faster than views an equivalent distance from a single known view (Bülthoff & Edelman, 1992). Logothetis and Pauls (1995) demonstrated that many cells in the inferotemporal cortex of macaque monkeys responded preferentially to a small range of views around a previously seen view of a familiar object but not previously unseen views of the same object, providing some neurological plausibility, and more recent models (e.g. Riesenhuber & Poggio, 1999) have developed on that of Poggio and Edelman (1990) taking into account this and other subsequent findings.

1.8 Comparing visual and haptic object recognition

That such a specific issue as orientation-constancy should form a central point of investigation in visual object recognition suggests clearly that it may also form a fruitful avenue of exploration for haptic recognition. As discussed above, the physiological and behavioural evidence all suggests considerable overlap between both visual and haptic object recognition, and even the underspecified models of haptic object recognition outlined in section 1.2 allow for some specific predictions to be made regarding the role of orientation in haptic object recognition.

Under the *image-mediation* model, the haptic and visual systems share the same representations at all levels, and thus should exhibit the same orientation-dependencies. However, under the *direct-apprehension* model, the physiological apparatus for haptically accessing representations differs greatly from that of the visual system. Haptics and vision only share representations at a higher, more abstract level. If the orientation-dependencies seen in visual object recognition are driven by lower level, modality-specific representations, then the orientation-sensitivity of the haptic system may differ from that of the visual system.

Nevertheless, there are other problems than viewpoint and orientation that must be overcome by the object recognition system, and thus to focus only on one specific topic would be to overlook the potential for new findings in a relatively under-studied modality. For reasons that will be discussed in greater detail later in the thesis, the topic of changes of size also seemed a good candidate for investigation. It is another issue that had previously been investigated in vision (e.g. Biederman & Cooper, 1992; Jolicoeur, 1987) and posed similar problems to the investigation of orientation-constancy.

As such, this thesis is broadly organized into two parts: Part I, consisting of Chapters 2, 3, and 4, examines the theme of attaining object constancy over orientation changes; Part II, consisting of Chapters 5 and 6, examines the effects of size changes on visual, haptic, and crossmodal object recognition. Chapters 2, 4, 5, and 6 are based on published articles; Chapter 3 is based on an article currently in press. Where possible, these chapters have remained as published or submitted. For the most part, those edits which have been made have been made to maintain consistent numbering of experiments across the thesis, to combine relatively general material from each chapter (such as elements of the introductions and discussions) into more appropriate sections of the thesis as a whole, and to forge clearer links to other Chapters. Only Chapter 5, which is based around the article Craddock & Lawson (2009a), required substantive revision. Craddock and Lawson (2009a) reports two experiments, the second of which was conducted by the second author without direction or analysis by the first author. This experiment has been entirely removed. An experiment which was conducted by the first author but remains unpublished has been added to the beginning of Chapter 5.

PART I| Haptic orientation sensitivity

CHAPTER 2| Repetition priming and haptic orientation-sensitivity

This chapter is adapted from Craddock, M., & Lawson, R. (2008). Repetition priming and the haptic recognition of familiar and unfamiliar objects. *Perception & Psychophysics, 70*(7), 1350-1365

2.1 Repetition priming and the haptic recognition of familiar and unfamiliar objects

Visual object recognition can be affected by changes in the orientation from which an object is perceived (see Lawson, 1999, for a review). Recent research has indicated that haptic object recognition may also display orientation-sensitivity (Newell et al., 2001; Forti & Humphreys, 2005; Lawson, 2009). In the present chapter, we investigate the susceptibility of the haptic system to manipulations of orientation. Although the terms "view" and "viewpoint" have been used previously in haptic studies (Forti & Humphreys, 2005; Newell et al., 2001), their meaning is not clearly specified in a haptic context. However, what constitutes a "view" depends on the orientation of the object with respect to the observer for both haptics and vision, so here the term orientation will be used.

2.1.1 Orientation effects in visual object recognition

Familiar objects are recognised best in a canonical, preferred orientation (Palmer, Rosch, & Chase, 1981). This may reflect early stages of visual processing, and be a function of the ease with which a particular image can be encoded, rather than being attributable to an object-specific, long-term representation (Lawson & Humphreys, 1998). The orientation-sensitivity of object-specific priming of visual object recognition based on stored representations has been a matter of extensive debate (see Lawson, 1999, for a review).

In Biederman's (1987) recognition-by-components model of visual object recognition, objects are assumed to be segmented into their constituent parts, and are represented by a description of those parts and their relations to each other. According to this model, recognition should be orientation-independent: as long as an object's parts and their relations are observable, recognition is independent of the specific viewpoint of the observer and of the orientations from which that observer has previously seen the object. Biederman and Gerhardstein (1993) found evidence of orientation-invariance in the priming of naming of pictures of familiar objects across depth rotations, and in the classification of novel, unfamiliar objects. In both cases they argued that this was due to the availability of the same structural description of an object for both study and test orientations.

Biederman and Gerhardstein (1993) suggested that entry-level, everyday object recognition would usually be orientation-invariant. They argued that orientation-dependence would only occur in a limited set of circumstances, such as when recognition took place at the subordinate level. However, contrary to their predictions, numerous studies have demonstrated orientation-specific priming at the entry level of recognition. The identification of an object is primed more when repeated presentations are in the same orientation than a different orientation (e.g., Lawson, 1999; Lawson & Humphreys, 1996, 1998, 1999; Thoma & Davidoff, 2006; Vuilleumier et al., 2002). The orientation-invariance reported by Biederman and Gerhardstein (1993) may be due to the low reliability of implicit measures such as name priming tasks. Several attempts have been made to understand what determines whether object identification is orientation-sensitive (e.g., Hayward, 2003; Stankiewicz, Hummel, & Cooper, 1998; Tarr & Cheng, 2003); the theoretical interpretation of orientation-sensitivity of visual object recognition will not be discussed further here.

2.1.2 Orientation effects in haptic object recognition

If the haptic system is sensitive to orientation when engaged in the recognition of real, 3D objects, this would be consistent with the hypothesis that representations are shared between haptics and vision, and that, in both modalities, object recognition is mediated by orientation-dependent mechanisms. If haptic recognition is orientation-invariant then this might be because the haptic system is not attuned to orientation, or that it compensates for the effect of orientation better than vision. It would also suggest that the representations shared between vision and haptics are orientation-independent.

Most experiments conducted on haptic object recognition have not explicitly controlled or manipulated orientation and, instead, have permitted bimanual, free exploration (e.g. Ballesteros, Reales, & Manga, 1999; Klatzky et al., 1985; Reales & Ballesteros, 1999). As Newell et al. (2001) observed, an intuitive suggestion might be that the haptic representation of objects would be omnidirectional since the thumbs and fingers of each hand can contact different sides of an object simultaneously, whereas the eyes can only see one side of an object at once. However, four recent studies have all indicated that haptic object recognition is sensitive to orientation (Forti & Humphreys, 2005; Lacey et al., 2007; Lawson, 2009; Newell et al., 2001).

Newell et al. (2001) compared visual and haptic recognition of unfamiliar stimuli constructed from stacked plastic bricks. Recognition both within- and across-modalities exhibited orientation-specificity. Within-modal recognition was best when no change of orientation occurred from study to test. In contrast, cross-modal recognition was best when objects were rotated back-to-front between study and test. Newell et al. (2001) argued that this pattern of results was due to the haptic system preferring the back of objects whereas the visual system prefers the front. However, this finding was for unfamiliar objects, for which the back and front were specified only within the confines of the experiment. It may not extend to objects that have a true back and front. Furthermore, Newell et al.'s (2001) stimuli were all constructed from the same parts; only their spatial configuration changed. The objects had the same material, temperature, and compliance, and thus did not encompass the wide variety of shapes and materials encountered in everyday recognition of familiar objects. If these cues are important for haptic object recognition, as Lederman et al. (1990) argue, Newell et al.'s (2001) findings may lack ecological validity.

Lacey et al. (2007) found that performance on a haptic and visual identification task in which participants learnt to associate wooden blocks (similar to the plastic blocks of Newell et al., 2001) with a number and then identified objects by number at subsequent presentations was orientation-sensitive within-modally but not cross-modally. The authors suggested that cross-modal identification was driven by orientation-independent representations, while within-modal identification was driven by orientation-dependent but modality-specific representations. Thus, haptic and visual orientation-sensitivity may be produced by different mechanisms, and may manifest differently in the two modalities. However, similar criticisms of ecological validity apply to the stimuli used by Lacey et al. (2007) as to the stimuli used by Newell et al. (2001).

Forti and Humphreys (2005) presented neuropsychological evidence from a study of cross-modal visuo-haptic matching. Their patient, JP, exhibited specific deficits in the retrieval of semantic information about objects, but was relatively good at accessing perceptual information. JP studied familiar, real objects haptically. The objects were obscured from view and attached to a support so that they could only be explored in one orientation. With both real objects and clay models of the objects, JP was better at matching visual presentations of a haptically studied object when it was in the same orientation at both study and test. Thus, cross-modal matching was best when there was no orientation-change, contrary to Newell et al.'s (2001) finding that cross-modal recognition improved with a 180°

orientation change and also contrary to Lacey et al.'s (2007) report of orientation-invariant cross-modal identification (see also Jüttner, Müller, & Rentschler, 2006). One reason for this discrepancy may be because familiar objects typically have front and back orientations outside of any experimental context, whereas the unfamiliar stimuli used by Newell et al. (2001) and Lacey et al. (2007) did not.

Finally, Lawson (2009) used a sequential-matching task to examine how the difficulty of detecting shape-changes might interact with orientation-changes in the haptic modality. Participants were presented with plastic, 3D models of familiar objects and morphs of midpoint shapes between two similar endpoint familiar objects, such as a midpoint shape between a bed and a chair. On match trials, the same object was presented twice either in the same orientation both times, or rotated in depth by 90° from the first to the second presentation. On mismatch trials, two different-shaped objects were presented at either the same or different orientations. The similarity of the mismatch objects was varied to manipulate the difficulty of shape discrimination in the task. Participants were asked to detect whether a shape-change had occurred. Orientation changes and discrimination difficulty affected both visual and haptic performance. In vision, the two factors interacted: the negative effects of orientation-changes were greatest when shape discrimination was hardest. However, in haptics, these two factors did not interact: the negative effects of orientation-changes stayed constant across all levels of shape discrimination. This difference in the observed pattern of orientation-sensitivity across matched studies, which varied only the modality of presentation, suggests that orientation-dependency may have different causes for visual and haptic object recognition.

These findings leave two main questions unanswered with respect to the effect of orientation on haptic object recognition. First, does orientation-dependence extend to the recognition of real, familiar objects? Newell et al.'s (2001) and Lacey et al.'s (2007) experiments demonstrating orientation-dependence with unfamiliar objects differed quite markedly from both everyday object recognition and previous experiments testing visual object recognition. Lawson's (2009) experiment used 3D plastic models of familiar objects, which, like the stimuli used by Newell et al. (2001), lacked many of the cues to identity present in everyday objects, such as size and texture. These cues are likely to be orientation-invariant, and thus may permit the orientation-invariant recognition of real objects. Second, do familiar objects have preferred, canonical orientations when being recognised haptically, as is found visually (Palmer et al., 1981)? Forti and Humphreys (2005) specified that objects were felt in canonical and non-canonical orientations but they did not test whether the canonical orientation was better recognised haptically. In addition, Forti and Humphreys' (2005) data came from a single neuropsychological case study, so it is important to test a large group of non-brain-damaged participants to establish the generality of their results.

2.2 Experiment 1

The effect of orientation-changes on priming of naming of familiar objects has not been systematically investigated in the haptic modality. Only Lawson (2009) and Forti and Humphreys (2005) have tested recognition of familiar objects following orientation-changes. Lawson (2008) found orientation-sensitive performance but she only tested plastic, scale models of real objects. Forti and Humphreys' (2005) participant, JP, displayed orientation-dependent performance, but this was only demonstrated in a cross-modal haptic to visual matching task. Neither a unimodal, haptic-haptic matching condition nor a neurologically-normal control group were tested. Furthermore, both Lawson (2008) and Forti and Humphreys (2005) used sequential matching tasks that only required object representations to be maintained for a few seconds. In contrast, Experiment 1 examined longer-term priming using a naming task with, on average, 15 minutes between presentations of a given item.

Previous experiments demonstrating significant within- and cross-modal priming of naming of familiar objects did not manipulate orientation (e.g., Reales & Ballesteros, 1999).

In Experiment 1, blindfolded, sighted participants identified familiar objects using bimanual, haptic exploration. Each object was presented in one of two (“easy”, canonical, or “hard”) orientations in the first block. In the second block, each object was presented again either at the same orientation as in the initial, priming block, or at a different orientation. Additionally, a set of familiar objects that had not been presented in the first block was presented in the second block. Naming of these new items was compared to naming of block 1 objects and primed objects in block 2 to check if participants showed any general improvement at naming objects from the first to the second block. If the representations used to recognise the primed objects were orientation-specific, then objects for which no orientation-change occurred from study to test should exhibit enhanced priming relative to objects for which an orientation-change occurred. However, if the mechanisms used to recognise the objects were orientation-invariant, there should be no cost associated with a change in orientation from study to test.

2.2.1 Method

Participants

Twenty-eight participants were drawn from the student population of the University of Liverpool either voluntarily or in return for course credit. Of those, 26 were female, and five were left-handed. A further two right-handed participants were recruited opportunistically. Ages ranged from 18 to 66 (M = 23 years). No participant in the studies reported here took part in more than one experiment.

Stimuli

Forty-five familiar objects were presented, see Appendix I. A further five familiar objects were used as practice items. Each object was glued to a 20 cm^2 ceramic tile (see Figure 2.1). Each object was assigned an easy, canonical orientation, chosen to represent a position in which the object would typically be experienced when using it with the right hand and when encountering it visually. Easy orientations were then rotated either by 90° (32 items) or 180° (13 items; see Appendix I) to yield a hard orientation. A full set of photographs of the familiar objects in their easy and hard orientations is included on the Supplementary CD.

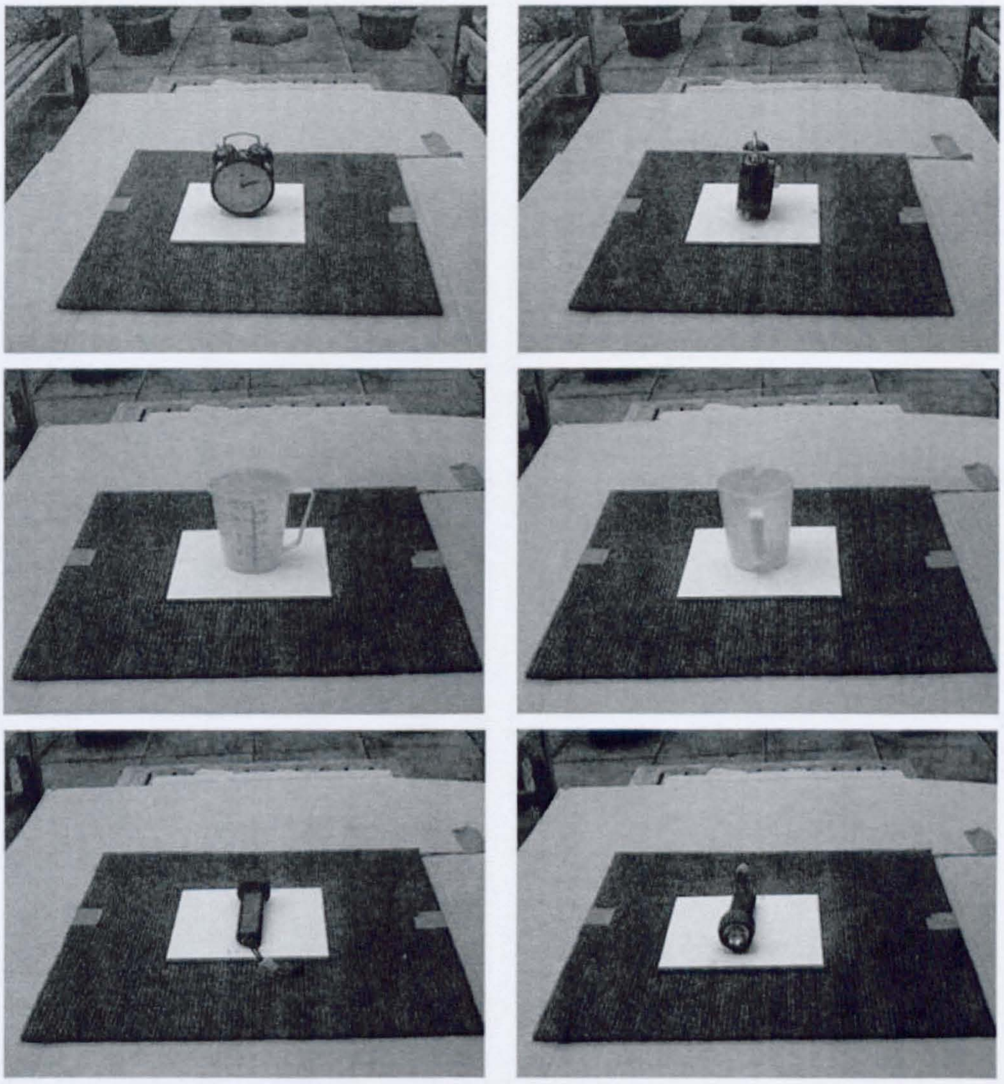

Figure 2.1. Photographs of the alarm clock, measuring jug, and torch used in Experiments 1 to 4. The left and right photographs show the easy and hard orientations respectively from the perspective of the participant.

Design and Procedure

The experimental objects were concealed behind a screen whenever participants were not blindfolded. Participants remained seated throughout the experiment. First, they named 20 line drawings of objects shown on a Macintosh computer monitor to familiarise them with the requirements of a vocal naming task. No objects that would appear in the haptic trials were shown. They were instructed to name the objects loudly and clearly, avoiding any unnecessary vocalizations.

Participants were then told that they would be required to name a series of objects by touch alone. They were shown the 50 cm^2 carpet tile on which the objects would be placed and the starting positions in which they should place their hands. These were indicated by pieces of masking tape at the centre of the left and right edges of the carpet tile (see Figure 2.1). The tape allowed participants to locate the starting hand positions consistently without vision. Carpet tile was used to muffle sounds made by placing of the objects and to minimise rotation of the objects after the experimenter had placed them. Participants then put on a pair of safety goggles covered in masking tape and confirmed that they were unable to see the area in which the objects would be placed.

Participants completed a block of five trials with the practice objects, then a block of 36 priming trials, and then a second block of 45 target trials. Participants were given a brief break between the two experimental blocks, and were not informed that objects would be repeated. During the break, the objects were hidden and participants were allowed to remove the goggles. Objects were split into five sets of nine, and allocated such that those expected to be particularly difficult to name were spread evenly throughout the sets, and each set contained objects with a similar variety of shapes and materials, see Appendix I.

Participants were allocated to five groups of six. Each group was required to name four of the five sets of objects in the first block and all five sets in the second block. Two of the four sets presented in the first block were at easy orientations and two were at hard orientations. One of each of these pairs of sets was presented in the same orientation in the second block, and the other was presented in the different orientation. The fifth set of objects was presented only in the second block. The object sets assigned to each group were rotated using a Latin Square design such that no two groups received the objects in the same combination (e.g. group 1 was the only group given set A in easy orientations in both experimental blocks). Each set of objects appeared in each of the five conditions an equal number of times.

The experimental software package PsyScope 1.2.5 (Cohen, MacWhinney, Flatt, & Provost, 1993) generated a random order of presentation of objects within each block and was used to record responses. The experimenter placed an object in the centre of the carpet tile in the appropriate orientation, and then started each trial once the participant had positioned their hands on the tape markers. A single low-pitched warning beep was played, followed by a high-pitched double-beep 1s later to indicate that participants could start to touch the object. They were instructed not to reposition or lift the objects. Participants were given unlimited time to name each object aloud, but were instructed to do so both quickly and accurately. Each trial ended when participants named the object or declared that they did not know its name. Response times were recorded using a microphone headset attached to a Macintosh computer as a voice key. The experimenter recorded incorrect responses, voice key errors, and trials on which the participants moved at the wrong time (movement errors).

2.2.2 Results

Participants identified objects correctly on 95% of all trials, including trials later excluded from the analysis due to voice key errors. Two participants were replaced as voice key errors occurred on over 20% of trials, and one was replaced as their median reaction time (RT) was over 8 seconds. Trials were excluded from RT analyses if a voice key error occurred (6% of trials), a movement error was made (1%), or an incorrect response was given (5%). Correct trials that presented an object for which an error occurred in the other block were also excluded (7%). Thus, for example, if an object was misnamed in block 2 but correctly named in block 1, RTs from both trials were excluded. Overall 81% of the data was included in the RT analyses.

Mixed analyses of variance (ANOVAs) were conducted on the median correct naming RTs and on the percentage of naming errors[1]. Experimental block (1 or 2), block 1 orientation (easy or hard), and block 2 orientation (easy or hard) were used as within-participants factors. Group was used as a between-participants factor in the by-participants analyses. Object set was used as a between-items factor in the by-items analyses. Effects involving these two counterbalancing factors are not reported. Post-hoc Tukey's HSD tests were conducted on significant interactions. *F*-values in the by-participants and by-items analyses are reported using subscripts F_p and F_i respectively. New items, which were presented in block 2 only, were analysed separately.

Priming from Block 1 to Block 2

There were significant main effects of block for both RTs [$F_p(1,25) = 64.477$, $p < .001$; $F_i(1,40) = 85.779$, $p < .001$] and errors [$F_p(1,25) = 19.082$ $p < .001$; $F_i(1,40) = 25.452$, $p < .001$]. Responses in block 2 (3130ms, 4% errors) were faster and more accurate than

[1] Analyses were also conducted using several different transformations to normalize RTs, including logarithmic and inverse transformations. None of these methods yielded different results to those reported here.

responses in block 1 (4263ms, 7%). There was substantial priming of naming in block 2. New items, which were presented in an easy orientation and in block 2 only, were recognised neither faster (4102ms) nor more accurately (7% errors) than items presented in easy orientations in block 1 (4040ms, $t(29) = 0.309$; 6% errors, $t(29) = 0.384$, $p = .7$). Furthermore, these new items were named significantly slower than primed items presented in easy orientations in block 2 (2984ms, $t(29) = 8.167$, $p < .001$); and they tended to be named less accurately than primed items in block 2 (4% errors, $t(29) = 1.648$, $p = .11$). Thus, there was no evidence that the increased speed and accuracy of naming of primed objects in block 2 was due to a general improvement of participants at the task from the first to the second block. Instead, the substantial priming observed was object-specific.

Effects of Easy/Hard Orientation

Block 1 orientation. In the by-participants analysis, there was a significant Block × Block 1 Orientation interaction for both RTs [$F_p(1,25) = 8.4$, $p = .008$] and errors [$F_p(1,25) = 6.126$, $p = .02$], see Figure 2.2. In the by-items analysis, this interaction was not significant for RTs [$F_i(1,40) = 0.635$, $p = .43$] but it was marginally significant for errors [$F_i(1,40) = 4.104$, $p = .049$]. Post-hoc Tukey's HSD tests revealed that in block 1, objects presented at easy orientations were recognised significantly faster and more accurately (4041ms, 6%) than objects presented at hard orientations (4485ms, 8%). However, in block 2, there was no significant difference between objects that had previously been presented in easy (3094ms, 4%) versus hard (3165ms, 3%) orientations. Thus, block 1 orientation influenced block 1 naming but not block 2 naming.

Block 2 orientation. There was a significant Block × Block 2 Orientation interaction for RTs [$F_p(1,25) = 5.091$, $p = .03$; $F_i(1,40) = 5.037$, $p = .03$] but not for errors [$F_p(1,25) = 1.086$, $p = .3$; $F_i(1,40) = 1.093$, $p = .3$]. Post-hoc Tukey's HSD tests did not find any significant difference between objects which would be presented at easy versus hard orientations in block 2 for block 1 responses (4264ms and 4261ms respectively) or block 2 responses (2984ms and 3275ms). However, consistent with the results from block 1, there was a trend for easy orientations in block 2 to be named around 300ms faster than hard orientations. Thus, block 2 orientation tended to influence block 2 naming and was not a carry-over effect from block 1 naming.

Effects of Orientation Changes from Block 1 to Block 2

Most importantly, the Block × Block 1 Orientation × Block 2 Orientation interaction was not significant for RTs [$F_p(1,25) = 0.078$, $p = .78$, see Figure 2.2; $F_i(1,40) = .55$, $p = .46$] or for errors [$F_p(1,25) = 1.818$, $p = .19$; $F_i(1,40) = 3.959$, $p = .054$]. The marginally significant effect for errors in the items analysis is consistent with orientation-specific priming. However, overall, participants recognised primed objects as quickly and nearly as accurately if there had been an orientation-change from block 1 to block 2 (3158 ms, 3% errors) as if there had not (3101 ms, 4%).

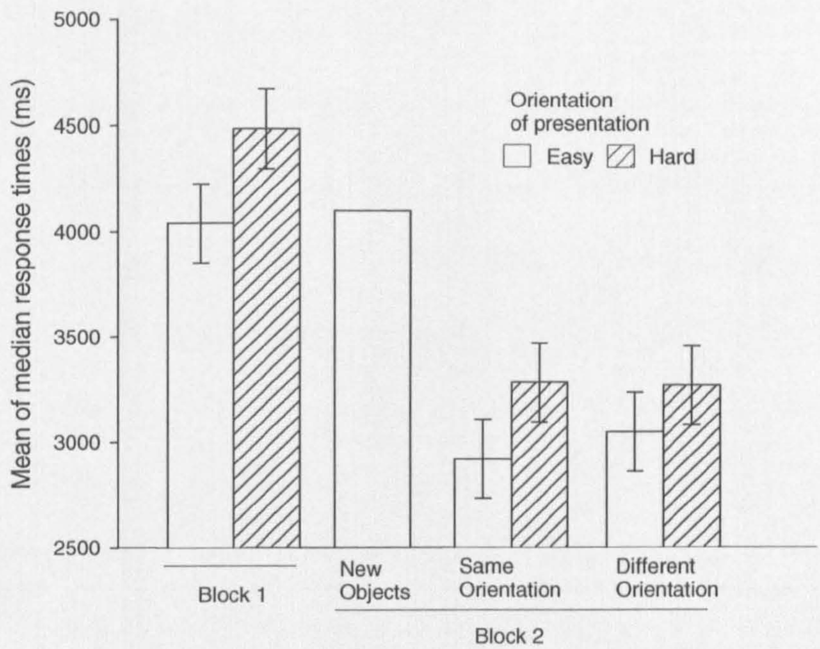

Figure 2.2. Mean of median RTs (by-participants) when naming objects presented at easy or hard orientations in blocks 1 and 2 (n = 30). Error bars represent 95% within-participant confidence intervals calculated using the error term of the Block × Block 1 Orientation × Block 2 Orientation interaction (Loftus & Masson, 1994). Error bars are omitted for new objects, as they were not included in the main ANOVA.

Axis of Elongation

An additional factor suggested by an anonymous reviewer was that canonical views for haptics might be related to the main axis of elongation of an object. Axis of elongation was not explicitly controlled, but objects were always placed such that it was always either parallel or perpendicular to the trunk of the observer. In a post-hoc analysis, we compared naming RTs from block 1 for objects in parallel versus perpendicular orientations. Only data from the 32 objects which were presented in both parallel and perpendicular orientations were included, see Appendix I. The analysis excluded the 13 objects for which easy and hard orientations were both parallel or both perpendicular due to a 180° easy-to-hard orientation change. Objects presented in parallel orientations were named faster (3932ms) than objects in perpendicular orientations (4880ms; $t(31) = -4.279$, $p < .001$). Since most easy orientations were parallel to the trunk of the observer the orientation of the main axis of elongation may, therefore, have caused the superior recognition of objects from easy orientations.

2.2.4 Discussion

First, these results replicated Klatzky et al.'s (1985) finding that 3D haptic object recognition can be both fast and accurate. The present findings extend these results by showing that initial recognition is also influenced by orientation. Objects presented at easy, canonical orientations were named faster and more accurately than those presented at hard orientations. Second, there was significant priming of naming, with objects being named faster and more accurately the second time compared to the first time that they were presented. This priming was not merely due to general improvement at the haptic identification task since it was object-specific. New objects presented in the second block were not named faster than objects presented in the first block and they were named slower than primed objects in the second block. Third, this priming was invariant with respect to orientation: there was no cost to either RTs or accuracy associated with a change in orientation from study to test. This replicated Reales and Ballesteros' (1999) finding of strong unimodal haptic priming of naming, and extended it to show that such priming may be orientation-invariant.

The initial orientation-effects are probably caused by some orientations being more informative than others, leading to faster identification. Easy haptic orientations may be similar to the canonical orientations documented in vision (Palmer et al. 1981), whereas hard haptic orientations may be analogous to what Biederman and Gerhardstein (1993) term "accidental views". Some features diagnostic of an object's identity are not readily available in these orientations. Visually, when a mug is oriented such that its handle is occluded, it may be harder to recognise than when its handle is visible. Similarly, at hard haptic orientations, it may take longer to extract sufficient information for recognition to occur, even though all surfaces of an object were readily accessible from the hard views used in Experiment 1. A post-hoc analysis suggested that haptic orientations were more canonical when the main axis of elongation of an object was parallel rather than perpendicular to the trunk of the observer's body. However, this factor was not explicitly controlled for in Experiment 1, so further research is necessary to test this hypothesis.

The lack of a difference between same-orientation and different-orientation priming suggests that the representations used in the process of haptic object recognition may be orientation-invariant; there is no cost of an orientation change because there is no representation of orientation, and no specific orientation can therefore be primed. Note that this possibility is compatible with our finding of canonical orientation effects on initial recognition. Initial orientation effects may be due to relatively early stages of haptic object processing, whereas orientation-specific priming across several minutes must be due to the activation of relatively long-term, stable, object-specific representations. The lack of orientation-specific priming effects is, however, contrary to the findings of Newell et al. (2001), and Forti and Humphreys (2005), who reported superior sequential matching performance on same-orientation relative to different-orientation trials. One reason for this discrepancy may have been that information about object orientation is not stored long-term so it was simply not available by the second block of naming in Experiment 1. There is some evidence that haptic memory of objects may decay rapidly, over several seconds (Kiphart, Hughes, Simmons, & Cross, 1992). Experiment 2 examined this hypothesis, again with approximately 15 minutes between presentations of a given object in each block. Participants classified each object at test as being in the same or a different orientation to when it had been named at initial presentation.

2.3 Experiment 2

In Experiment 2, blindfolded, sighted participants named familiar objects in easy or hard orientations. In an unexpected test block, participants then decided whether each object was in the same orientation as it had been at study or in a different orientation. If the haptic system had not formed a stable, persistent orientation-dependent representation, participants should not be able to accurately accomplish this task.

2.3.1 Method

Participants

Ten right-handed students of the University of Liverpool participated in return for course credit. Eight were female. Ages ranged from 18 to 22 (M = 19 years).

Stimuli

The same stimuli were used as in Experiment 1.

Design and Procedure

Experiment 2 replicated Experiment 1 except for the following points. In block 2, participants stated whether the object was presented at the same or a different orientation than it had been in block 1. No new items were introduced in block 2. Participants were informed that block 2 would be a same-different orientation task during the break between block 1 and block 2, and thus they did not know during block 1 that they would be required to remember the orientation in which the objects were presented.

2.3.2 Results

One participant was replaced as voice key errors occurred on over 20% of trials. Naming in block 1 was similar to naming in block 1 of Experiment 1 (4053ms, 8% errors). In block 2, participants identified whether an orientation change had occurred from study to test quite accurately. Single sample t-tests indicated that same-orientations (M = 88%, SD = 9%) were identified significantly above chance (μ = 50%, $t(9) = 14.318$, $p < .001$), as were different-orientations (M = 87%, SD = 10%; μ = 50%, $t(9) = 12.043$, $p < .001$).

2.3.3 Discussion

The results of Experiment 2 show that the orientation-invariant priming observed in Experiment 1 was not attributable to a failure to encode the orientation in which the object had been presented at study. Participants quite accurately classified objects as being in the same or a different orientation at test relative to at study. Thus, although participants were not informed that they were required to remember the orientation of the objects presented for naming at study until they were due to begin the test block, they formed orientation-sensitive representations of the objects.

Another reason for the lack of orientation-specific priming in Experiment 1 is that this priming may have been largely conceptual or semantic rather than perceptual. Such non-perceptual priming would not be expected to be associated with strong effects of orientation. Experiment 3 was conducted to determine whether a significant proportion of the priming observed in Experiment 1 occurred at haptic stages of processing.

2.4 Experiment 3

Reales and Ballesteros (1999) argued that the dissociation between the implicit and explicit tasks in their experiments indicated that the haptic and visual priming they observed was pre-semantic. Additionally, they found no modality-specificity in either implicit or explicit tasks. As noted earlier, their argument assumes that level of processing dissociates implicit and explicit memory, and that implicit memory primarily reflects perceptual priming. Lacey and Campbell (2006) argued that different representational codes, including a verbal code, could underpin cross-modal priming between vision and haptics. Thus, the priming of naming found by Reales and Ballesteros (1999) cannot be assumed to be purely pre-semantic.

The literature on haptic-specific priming has not been conclusive. Easton, Srinivas, and Greene (1997) found a marginally significant within-modality priming advantage in visual and haptic naming tasks, although there was no main effect of study modality on performance in either test modality. Bushnell and Baxt (1999) also found evidence for modality-specific representations, but used an old/new recognition task and thus provided no measure of priming. Furthermore, their study only assessed recognition by young children, who may display different recognition performance to adults.

We manipulated study modality in Experiment 3 to examine whether any of the priming observed in Experiment 1 was specific to the haptic modality. As in Experiment 1, participants named familiar objects. However, half of the objects were presented visually at study and half were presented haptically. At test, all objects were then presented haptically at easy orientations. As before, there were approximately 15 minutes between each presentation of a given object. Visual presentations were photographs of different exemplars of the familiar objects that would be presented at test. Similar semantic and conceptual information should be activated after naming an object presented visually or haptically: for example, a kettle has the same name and function whether it is identified by touch or by vision. If the priming observed in Experiment 1 were due solely to semantic or name priming, or to activation of bi-modal perceptual representations accessible from either vision or haptics, there should be no difference in performance at test attributable to study modality. However, if some component of the priming is specifically haptic, then haptic priming should be greater than visual priming.

2.4.1 Method

Participants

Thirty right-handed students aged 18 to 40 (M = 20 years) of the University of Liverpool participated in exchange for course credit. Twenty-five were female.

Stimuli

The haptic stimuli were those used in Experiments 1 and 2, see Appendix I. The visual stimuli were 45 photographs of different exemplars of each of the haptic object categories. The photographs were sourced from the internet, and depicted the objects in isolation and in canonical orientations. The photographs were resized to occupy an area of 300 x 300 pixels on the computer screen, and a full set is available on the Supplementary CD.

Design and Procedure

Objects were divided into three sets of 15 objects so that each set contained a similar variety of shapes and materials, see Appendix I. Participants were allocated to six groups of five. The first block consisted of two sub-blocks, with one object set being shown visually in one sub-block and another object set being presented haptically in the other sub-block. All three sets of objects were then presented haptically in the second block. Each group shared the same sets of objects with one other group: one was given the visual set followed by the haptic set, and the other group was given the haptic set followed by the visual set. A Latin Square design was used to counterbalance the allocation of object sets to groups.

The procedure for haptic trials was identical to Experiment 1 with the exception that objects were always presented in easy orientations. Since visual recognition of objects is faster than haptic recognition, the visually presented objects were shown twice to approximately equate the study time to that of the haptically presented objects in block 1. First, a photograph of each object was presented in the centre of the Macintosh computer screen for 2 seconds for participants to name. Second, a photograph of each object was presented for 1 second, and participants named one of the materials from which the object was made. This second presentation also encouraged participants to attend to at least one non-shape feature that would typically be perceived when haptically identifying an object. Appendix I lists accepted material names for each object.

Participants undertook 45 trials in block 1: 15 haptic naming, 15 visual naming, and 15 visual naming of object materials. Participants then named 45 objects in block 2: 15 haptically primed objects, 15 visually primed objects, and 15 unprimed objects. Participants were given a brief break between the two experimental blocks. On completion of the experimental trials, participants were read a list of the objects that had been presented during the experiment. Participants stated whether each object had been presented in block 1 either visually or haptically, or presented only in block 2.

2.4.2 Results

No participants were replaced in Experiment 3. Participants identified objects correctly on 96% of all trials, including those trials later excluded from the analysis due to voice key errors. Trials were excluded from RT analyses if a voice key error (4% of trials) or movement error (<1%) was made, or an incorrect response was given (4%). Trials that presented an object for which an incorrect response was given in the other block were also excluded (7%). Overall 84% of trials were included in the RT analyses. Block 1 data was not included in the main analysis; means of median naming RTs and mean percentage naming errors in block 1 were 1072ms and 1% errors for visual study and 4293ms and 5% errors for haptic study.

A mixed ANOVA was conducted on the median correct naming RTs and on the mean percentage of naming errors. Study modality (visual, haptic, or unstudied) was used as a within-participants factor. Group was used as a between-participants factor in the by-participants analysis. Object set was used as a between-items factor in the by-items analysis. Effects involving these latter two counterbalancing factors are not reported. *F*-values in the by-participants and by-items analyses are reported using subscripts F_p and F_i respectively. As the data in the by-items analysis violated the assumption of sphericity, Huynh-Feldt correction was applied.

There was a significant main effect of study type for RTs [$F_p(2,48) = 124.737$, $p < .001$, see Figure 2.3; $F_i(1.246,52.342) = 27.064$, $p < .001$] but not for errors [$F_p(2,48) = .389$, $p = .68$; $F_i(1.887, 79.248) = .387$, $p = .67$]. Haptically studied objects were named fastest (3149ms) followed by visually studied objects (3508ms). Unstudied objects were named slowest (4458ms). Pairwise comparisons using Bonferroni correction revealed that haptically primed objects were recognised significantly faster (359ms) than visually primed objects, which in turn were recognised significantly faster (977ms) than unstudied objects. Thus, approximately a quarter of the priming was specific to objects studied haptically rather than visually in block 1.

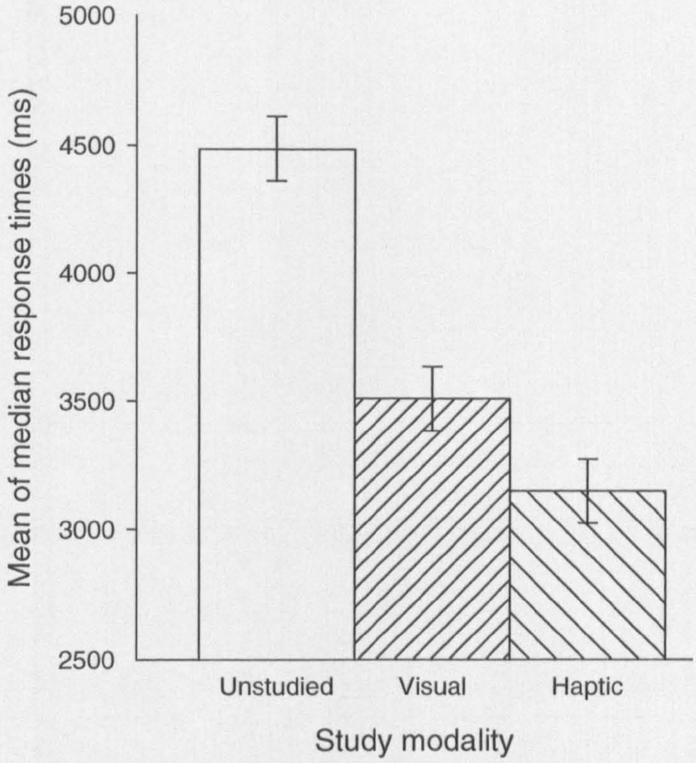

Figure 2.3. Means of median RTs (by-participants) by study modality when recognising objects haptically at test in Experiment 3 (n = 30). Error bars show 95% within-participant confidence intervals (Loftus & Masson, 1994).

The final part of Experiment 3 tested recall of original study modality. To account for response bias, d' scores were computed for each of the possible responses. Many participants scored 100% for at least one of the three response options, so scores were combined across participants. Misses were trials on which an object was misclassified as belonging to another condition. For example, a trial on which a visually studied object was classified as being unstudied or haptically studied was a miss trial for visually studied objects. The same trials were also false alarms for other conditions; thus, a trial on which a visually studied object was classified as being haptically studied was a false alarm trial for haptically studied objects. Participants were quite accurate at identifying the study modality of unstudied (83%, d' =

2.56), visually studied (84%, $d' = 2.85$), and haptically studied (92%, $d' = 2.58$) objects during the final part of Experiment 3.

2.4.3 Discussion

Substantial within-modal and cross-modal priming of naming was observed in Experiment 3: both haptically and visually studied objects were named faster than unstudied objects. Most importantly, haptically studied objects were named faster than visually studied objects. Thus, whilst a substantial component of the observed priming could be explained by semantic, verbal, or bimodal (visual/haptic) representations, a significant component, around 360ms, could not. Unlike the complete cross-modal transfer observed between the visual and haptic modalities observed by Reales and Ballesteros (1999), here we found an advantage for objects studied haptically at both study and test. Note that this result is not necessarily contrary to their findings. The same 3D exemplars were seen and felt from the same vantage point in the study conducted by Reales and Ballesteros (1999), whereas different exemplars of objects were shown from different orientations for visual and haptic presentation in Experiment 3. This introduced differences beyond the change in modality.

Although the difference we observed between haptic and visual priming might be attributable to several factors – the change of modality or exemplar, or the change from 2D to 3D – all of these factors alter the perceptual input whilst keeping the semantic information and verbal label the same. Therefore, the main reason why an advantage was found for haptic priming must be that a significant proportion of priming here – and in Experiment 1 – was mediated by long-term, object-specific perceptual representations.

Participants could quite accurately identify the study modality of each object, indicating that the source of the memory was stored. Even if some of the priming observed in this study was underpinned by bi-modal representations derived from haptics and/or vision, these results demonstrate that information about input modality is available. Thus, either the bi-modal representations are qualitatively different according to study modality, which seems unnecessary given that they may be relatively abstract representations of shape, or additional, modality-specific episodic markers exist. Another possibility is that, rather than the existence of a specific marker indicating the source modality of a given input, the combination of several modality-specific features may indicate the source of the representation. For example, if the colour of an object is remembered then it must have been studied visually.

2.5 Experiment 4

We have established that the lack of orientation-sensitivity found in Experiment 1, in a long-term name priming task, was not due to people failing to code object orientation (Experiment 2), nor to the priming being non-perceptual (Experiment 3). Experiment 4 therefore returned to the question that we initially posed. Is the haptic recognition of familiar objects dependent on the orientation at which they are presented? We addressed this issue by presenting unfamiliar as well as familiar objects in a potentially more sensitive task, that of old/new recognition, whilst still testing for long-term orientation-specificity (cf. Forti & Humphreys, 2005; Lacey et al., 2007; Lawson, 2009).

Orientation-effects should be easier to detect in tasks that maximise the involvement of perceptual representations and reduce the influence of other factors such as semantics, since non-perceptual representations are unlikely to exhibit orientation-sensitivity. The results of Experiment 3 suggested that much of the priming observed in Experiment 1 may have been non-perceptual, and so it may not have provided a sensitive test of orientation-effects. To test this possibility, in Experiment 4 we presented unfamiliar as well as familiar objects. Unfamiliar objects lack semantic, conceptual representations, and so orientation-effects may be easier to detect using such stimuli.

An alternative reason for the lack of orientation-sensitive priming in Experiment 1 may have been that orientation-invariant, non-shape features such as texture or temperature drove the perceptual priming in that study. In this case, performance with unfamiliar objects with similar orientation-invariant features to familiar objects should also be orientation-invariant. Such invariant features could not be used to identify objects in Newell et al.'s (2001), Lacey et al.'s (2007), and Lawson's (2009) experiments since all of their stimuli were made from the same material. Forti and Humphreys (2005) only tested transfer from haptic study to visual object recognition, so orientation-invariant haptic features such as temperature were not useful at test. Therefore, in all four studies that have reported orientation effects on haptic object recognition, orientation-dependence may have been due to the absence of informative orientation-invariant features, whilst orientation-invariance in Experiment 1 may have been due to their presence. Since such features are normally available for everyday haptic object recognition, it is important to establish whether orientation effects can be observed for objects possessing orientation-invariant features.

The long-term name priming task used in Experiment 1 also differed from previous studies that found orientation-dependence in haptic object recognition. These studies measured performance on shorter-term matching (Forti & Humphreys, 2005; Lawson, 2009) and in old/new recognition and identification tasks (Lacey et al., 2007; Newell et al., 2001). As noted earlier, the reliability, and, therefore, the power and sensitivity, of implicit measures such as priming of naming has been questioned (Buchner & Brandt, 2003; Buchner & Wippich, 2000; Meier & Perrig, 2000). It is therefore possible that the discrepancy between the results of Experiment 1 and earlier studies (Forti & Humphreys, 2005; Lacey et al., 2007; Lawson, 2009; Newell et al., 2001) was due to its use of a relatively insensitive measure.

The influence of object familiarity, the presence of non-shape orientation-invariant features, and the use of a potentially more reliable task than name priming were examined in

Experiment 4. We used an old/new recognition task to assess orientation-sensitivity for familiar and unfamiliar objects. Participants first studied half of the familiar and unfamiliar objects presented at either easy or hard orientations. They then classified all of the familiar and unfamiliar objects as being either previously studied (old) or new. Half of the old objects were presented in the same orientation at study and test, and half changed orientation from study to test.

2.5.1 Method

Participants

Thirty-two students of the University of Liverpool participated in exchange for course credit. Of these, 19 were female, and two were left-handed. Ages ranged from 18 to 35 (M = 20 years).

Stimuli

The 32 familiar objects were a subset of those used in Experiments 1 to 3, see Appendix I. A set of 32 unfamiliar objects was then produced, each of which was approximately matched to a familiar object in shape, size, texture and material, see Figure 2.4. The unfamiliar objects included unusual, difficult to name objects and common objects modified to be difficult to recognise. For example, one unfamiliar object was a computer hard drive with a section of its casing removed; another was an ice-cream scoop that was bent in two places to leave a hole in the middle of the scoop and an unusually shaped handle, and then had an extra piece of plastic glued on. A full set of photographs of the unfamiliar objects is available on the Supplementary CD. Each unfamiliar object was glued to a 20 cm^2 ceramic tile so that its main axis of elongation was oriented in the same way as its matched familiar object. The same easy and hard orientations were assigned to it as for its matched familiar object based on this axis.

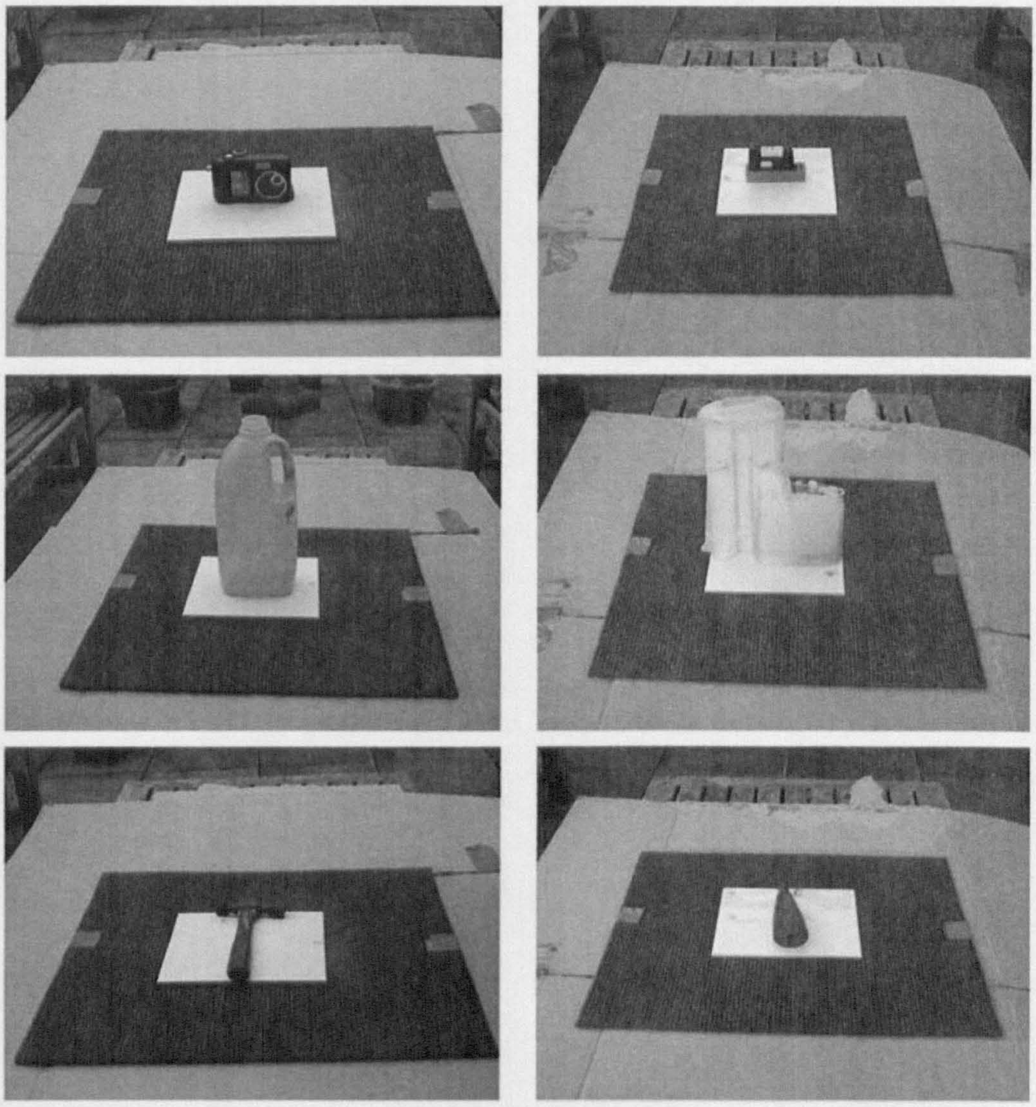

Figure 2.4. Photographs of matched pairs of familiar (left) and unfamiliar (right) objects both placed in easy orientations. Pictured from top to bottom are a camera and printer cartridge, a milk bottle and part of the plumbing of a toilet cistern, and a hammer and part of a chair leg sawn in half.

Design and Procedure

To establish that the unfamiliar objects were indeed novel, five participants who did not take part in Experiment 4 tried to identify them haptically. Forty unfamiliar objects were presented sequentially, together with five familiar objects that were included to check that people were trying to do the task. Only unfamiliar objects that were given no name or very different names by at least three of the participants were used in the main experiment. Objects were divided into eight sets, with four familiar and four unfamiliar objects in each set, and a similar variety of shapes and materials in each set, see Appendix I.

Participants were allocated to eight groups. Each group was assigned four sets of objects to be the old items that were presented in both experimental blocks. Two of these sets were presented in easy orientations in the study block and two in hard orientations. Of each of these pairs of sets, one was presented in the same orientation at study and test, and the other set was presented in a different orientation at study and test. The other four sets of objects were presented only once as the new items in the test block. Two of these new sets were presented in easy orientations, and two in hard orientations. The object sets assigned to each group were rotated using a Latin Square design such that no two groups received the same combination of sets. Each object appeared in all possible combinations of orientation and orientation change an equal number of times.

Each trial was identical to the haptic trials in Experiment 1 except for the following points. Study trials were limited to five seconds, after which a single high-pitched beep indicated that the participant should stop exploring the object. Participants were told to explore each object for the full five seconds, and not to make any response. They were told that they would be asked to remember the objects later in the experiment. Study trials were presented in a random order.

In test trials, participants were allowed unlimited time to explore each object. They stated whether it was an "old" object – one that had previously been studied – or a "new" object – one that had not appeared in the study phase. Each trial ended when the participant responded. Objects were presented in the same order for all participants. Thus, the order of conditions in the test block was pseudo-randomly mixed.

Participants were given a block of 32 study trials comprising eight familiar and eight unfamiliar objects in easy orientations and eight familiar and eight unfamiliar objects in hard orientations. They then completed a block of 64 test trials, comprising 16 familiar and 16 unfamiliar new objects, 8 familiar and 8 unfamiliar old objects in the same orientation as in the prime block (half at easy and half at hard orientations), and 8 familiar and 8 unfamiliar objects in a different orientation to that presented in the prime block (half at easy and half at hard orientation). Participants were given a brief break between the study and test blocks.

2.5.2 Results

Four participants were replaced as voice key errors occurred on over 20% of trials. Trials were excluded from RT analyses if a voice key error (4% of trials) or movement error (1%) was made, or an incorrect response was given (16%). F-values in the by-participants and by-items analyses are reported using subscripts F_p and F_i respectively.

The effect of the initial orientation (easy or hard) on recognition memory was not tested in these ANOVAs, as each orientation was not presented enough times and this issue was not the focus of interest in Experiment 4. However, the overall results were consistent with our finding of a benefit for canonical orientations in Experiment 1. At test, recognition memory for easy orientations was around 150-200ms faster than that for hard orientations. Mean values for the easy and hard orientations were as follows: old familiar objects, 3065ms and 3229ms respectively; old unfamiliar objects, 4300ms and 4472ms; new familiar objects, 3950ms and 4131ms; new unfamiliar objects, 4789ms and 4990ms. There were no overall effects on errors.

Mixed ANOVAs were conducted on RTs and percentage errors. In the by-participants analyses, familiarity (familiar or unfamiliar) and orientation (same or different) were within-participants factors, and group was a between-participants factor. In the by-items analyses, orientation was a within-items factor, while familiarity and object set were between-items factors. Effects involving the counterbalancing factors of group and object set are not reported.

There was a significant main effect of familiarity for RTs [$F_p(1,24) = 47.126$, $p < .001$; $F_i(1,48) = 51.487$, $p < .001$] and errors [$F_p(1,24) = 37.934$, $p < .001$; $F_i(1,48) = 27.758$, $p < .001$]. Old, familiar objects were recognised faster (3209 ms) and more accurately (9% errors) than old, unfamiliar objects (4352 ms, 29%).

There was a significant main effect of orientation for RTs by-participants but not by-items [$F_p(1,24) = 5.304$, $p = .03$; $F_i(1,48) = .357$, $p = .55$], and for errors [$F_p(1,24) = 8.294$, $p = .008$; $F_i(1,48) = 4.569$, $p = .038$]. Objects placed in the same orientation in both blocks were recognised faster and more accurately (3646 ms, 16% errors) than objects placed in different orientations (3916 ms, 22%).

Importantly, there was no Familiarity × Orientation interaction for RTs [$F_p(1,24) = 0.385$, $p = .54$, see Figure 2.5; $F_i(1,48) = 3.026$, $p = .088$] or errors [$F_p(1,24) = 1.034$, $p = .32$, see Figure 2.6; $F_i(1,48) = .789$, $p = .38$]. Furthermore, the marginally significant effect for RTs in the by-items analysis reflected a trend for greater effects of orientation for the familiar compared to the unfamiliar objects. There was no evidence that orientation-specificity for old/new recognition was greater for unfamiliar objects, contrary to the predictions based on familiarity outlined earlier.

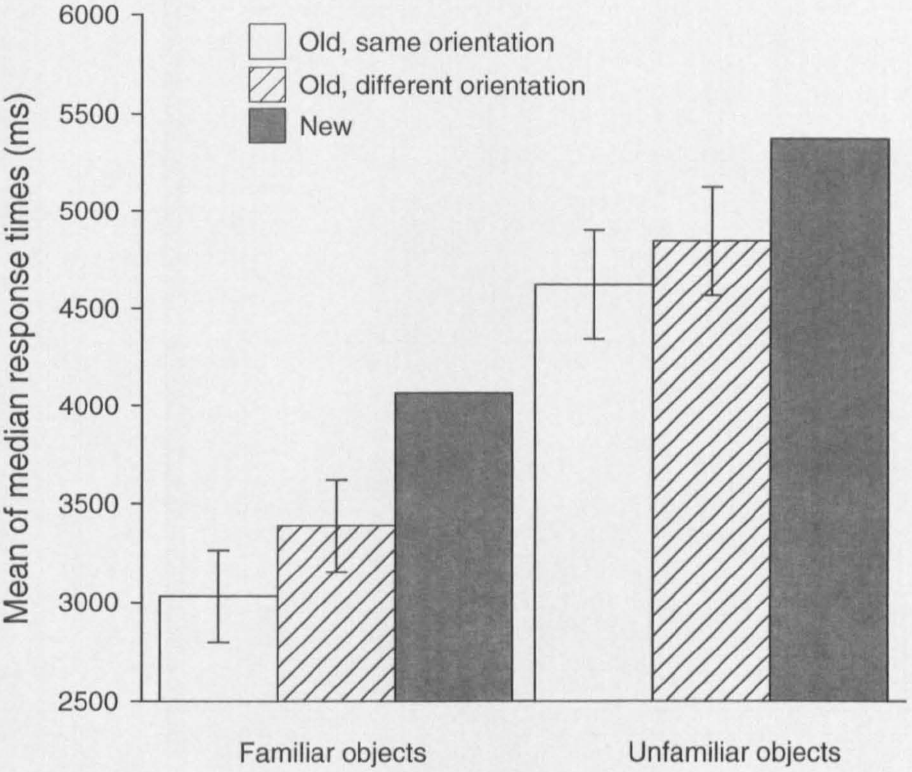

Figure 2.5. Means of median RTs (by-participants; $n = 32$) for recognition of familiar and unfamiliar objects separated by orientation at test (same or different). Error bars show 95% within-participant confidence intervals calculated using the error term of the Familiarity × Orientation interaction (Loftus & Masson, 1994). Error bars are omitted for new objects, as they were not included in the main ANOVA.

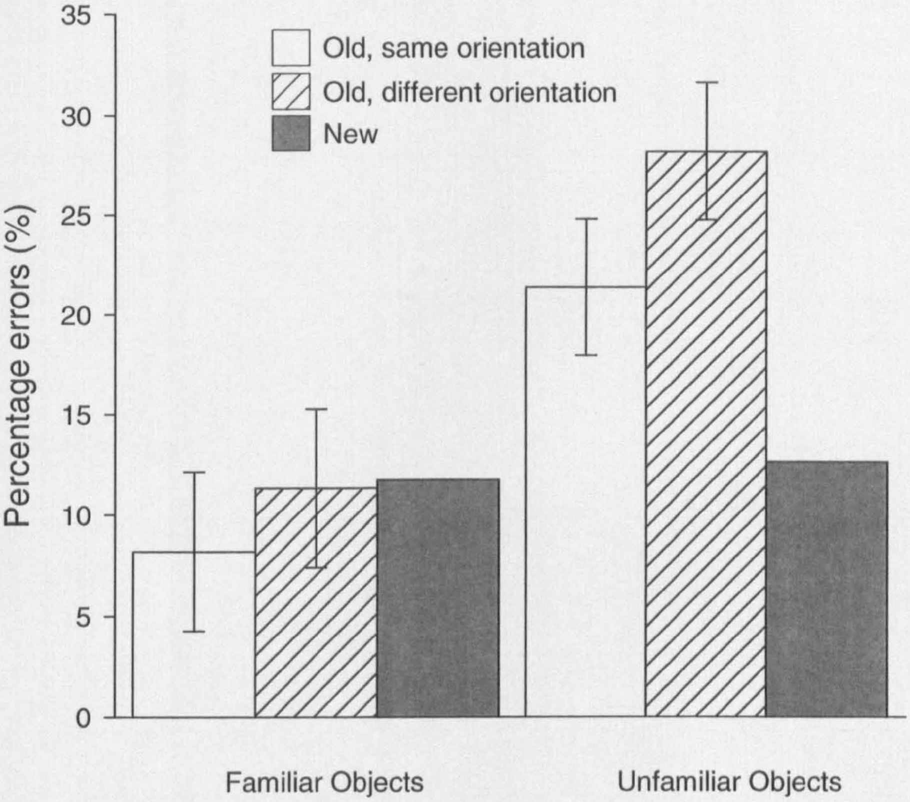

Figure 2.6. Mean percentage errors (by-participants; $n = 32$) of recognition of familiar and unfamiliar objects for new objects and for old objects separated by orientation at test (same or different). Error bars show 95% within-participant confidence intervals calculated using the error term of the Familiarity × Orientation interaction (Loftus & Masson, 1994). Error bars are omitted for new objects, as they were not included in the main ANOVA.

New objects were not included in the above analysis, since orientation was not a meaningful variable for objects only presented once. Means are reported here for completeness. Mean of median RTs and mean percentage errors for new familiar objects were 4065ms and 12%, while for new unfamiliar objects they were 4882ms and 14%.

2.5.3 Discussion

Firstly, both familiar and unfamiliar objects were recognised best when placed in the same orientation at study and test in comparison to when placed in different orientations. Secondly, although performance overall was both faster and more accurate for familiar objects than for unfamiliar objects, there was no interaction between familiarity and orientation-change. These results replicate similar findings for unfamiliar objects (Newell et al., 2001; Lacey et al., 2007) and for models of familiar objects (Lawson, 2009), and extend them to a much broader range of familiar and unfamiliar 3D objects possessing a variety of orientation-invariant cues such as temperature and texture.

The results of Experiment 4 contrast with the orientation-invariant priming of naming found for familiar objects in Experiment 1. These results demonstrate that it was not merely object familiarity per se that resulted in a lack of orientation sensitivity in our first study. Another explanation for orientation-invariance in Experiment 1 was that orientation-invariant cues such as texture and temperature drove priming. Previous reports of orientation-sensitive haptic-haptic object processing have used stimuli with uninformative cues to size and made of the same material (Lacey et al., 2007; Lawson, 2009; Newell et al., 2001). These studies used objects that did not have the variety of shapes and materials that characterise everyday objects, and which lacked at least some of the characteristics to which the haptic system is best attuned (Klatzky et al., 1987; Lederman & Klatzky, 1990). All the familiar objects that appeared in Experiment 4 were used in Experiment 1, and so the same features (e.g., texture) were present in both studies. The orientation-sensitive performance found in Experiment 4 shows that the presence of orientation-invariant cues cannot explain the lack of orientation effects found in Experiment 1. Nevertheless, orientation-invariant cues may have reduced orientation effects in all of the present studies, relative to objects lacking these features.

The failure to find orientation-sensitive effects in Experiment 1 may primarily have been due to the lower reliability and sensitivity of the name priming task compared to the old/new recognition task used in Experiment 4. Familiar object naming is quite fast and accurate, even for haptic presentation, so a ceiling effect may have masked any influence of orientation-changes in Experiment 1. However, old/new recognition of familiar objects in Experiment 4 was also quite fast and accurate, but it was still orientation-specific. A more likely cause of the difference between the two studies is that old/new recognition is a more powerful and sensitive measure of orientation effects than name priming (Buchner & Brandt, 2003; Buchner & Wippich, 2000; Meier & Perrig, 2000). Furthermore, the results of Experiment 3 suggest that much of the priming in Experiment 1 may have been non-perceptual, which would have contributed to the reduced sensitivity of the naming task to orientation changes in Experiment 1.

In Experiment 4, recognition overall was faster and more accurate for the familiar objects. The time allowed for study (5s) and the average RT at test (4s) was sufficient to allow covert naming of familiar objects in Experiment 4. Therefore, some of the benefit for familiar objects may have been due to people using semantic and naming information. While semantic descriptions of unfamiliar objects may still have been possible, they would typically be less specific, and therefore of limited value for recognition.

2.6 General Discussion

In Experiment 1, orientation changes did not influence the priming of the haptic recognition of familiar objects. Experiment 2 demonstrated that the null finding in Experiment 1 was not due to people failing to encode the orientation of haptically presented objects. Experiment 3 showed that a significant amount of the priming observed in Experiment 1 was specific to haptically studied objects, but that a substantial component of the priming was not modality-specific and was probably non-perceptual. Finally, Experiment 4 showed that orientation changes worsen performance on an old/new recognition task for both familiar and unfamiliar objects, consistent with the results of recent studies demonstrating haptic orientation-specificity (Forti & Humphreys, 2005; Lacey et al., 2007; Lawson, 2008; Newell et al., 2001).

Experiment 1 found clear evidence that some orientations of familiar objects were preferred haptically, resulting in faster and more accurate naming. Thus, familiar objects appear to have haptically canonical orientations analogous to visually canonical orientations (Humphrey & Jolicoeur, 1993; Lawson & Humphreys, 1998; Palmer et al., 1981). However, the results of Experiment 1 do not indicate whether the preferred orientations in haptics are the same as those in vision. Newell et al.'s (2001) finding that the haptic system prefers a back orientation with respect to the observer's head, in comparison to the visual system's preference for a front orientation, suggests that haptic and visual canonical orientations may differ. However, this does not necessarily mean that the visual and haptic systems use different representations. These effects may simply reflect differing biomechanical constraints on acquiring visual versus haptic information rather than modality-specific differences in coding object-specific representations from different orientations.

An object placed in its visual canonical orientation may not be at the optimum orientation for haptic recognition, and vice versa, since each modality may use a different reference-frame. Furthermore, the reference-frame used by haptics may change over time (Zuidhoek, Kappers, van der Lubbe, & Postma, 2003), and may be biased by the position of the head and eyes and the presence of non-informative vision (Zuidhoek, Visser, Bredero, & Postma, 2004). Additionally, the haptic system initially weights local features more heavily than global shape (Lakatos & Marks, 1999). Further research would be required to establish how canonical representations translate across modalities.

Priming of naming of familiar objects in Experiment 1 was not orientation-sensitive. Caution must be taken when failing to reject the null hypothesis, particularly since, in Experiment 4, recognition of both familiar and unfamiliar objects was found to be orientation-dependent. First, a null result may occur when a paradigm does not invoke the mechanisms that it is intended to test. Experiment 2 thus served as a manipulation check, showing that participants were encoding long-term orientation-dependent representations. Second, a null result may occur when a paradigm lacks sufficient power to detect an effect. As noted earlier, implicit measures such as name priming may be relatively unreliable (Buchner & Wippich, 2000; Meier & Perrig, 2000). Third, the results of Experiment 3 suggest that the priming of naming in Experiment 1 may have been predominantly driven by non-perceptual priming. However, old/new recognition memory was orientation-sensitive in Experiment 4. Perceptual representations may have exerted a more substantial influence on recognition performance in Experiment 4 than on name priming in Experiment 1, and thus orientation-sensitivity was easier to detect.

These experiments did not test the effect of orientation-changes on cross-modal object recognition. In part, this is due to the difficulty of equating orientation across modalities. For example, an object can be presented visually at a single, fixed orientation, whereas a haptically presented object is typically explored over several seconds using movements across several sides of an object. That orientation-dependence may still arise under such circumstances (Forti & Humphreys, 2005; Newell et al., 2001) is somewhat surprising.

Nevertheless, there still remained several factors which needed to be investigated with relation to haptic-specific orientation sensitivity. The first of these is how orientation-sensitivity progresses over time. This issue is addressed in Chapter 3, which varies ISI systematically. Second is whether haptic orientation-sensitivity is determined with respect to the hand used to explore the object or a more body-centred reference frame, and furthermore whether handedness in general has a role in haptic object recognition, and specifically naming. This is explored in Chapter 4, which varies exploration hand and object orientation.

CHAPTER 3| Effects of temporal delay and orientation changes

This chapter is adapted from Craddock, M., & Lawson, R. (in press). "The effects of temporal delay and orientation on haptic object recognition." *Attention, Perception, & Psychophysics*

3.1 The effects of temporal delay and orientation on haptic object recognition.

Inputs from vision and haptics are not equivalent and must first traverse separate pathways. Each modality will, therefore, be subject to its own limits and will exhibit differing performance in some tasks even if input from both modalities ultimately activates common perceptual representations. Although haptic object recognition can be reasonably fast (e.g., Klatzky et al., 1985; Craddock & Lawson, 2008, 2009a) it is still generally much slower than vision (e.g., Craddock & Lawson, 2009a). Its limits are most obvious in the recognition of 2D raised-line drawings; haptic exploration is often insufficient to recognise such drawings even given unlimited presentation time (Lederman et al., 1990), while vision can recognise them trivially. However, when vision is forced to operate under similar constraints to haptics, for example by limiting its field of view, it too performs poorly (Loomis et al., 1991).

Given that haptics relies on slower, more sequential exploration than vision to acquire the same amount of information, it must also depend more upon working and short-term memory to maintain and integrate the incoming information as it is accumulated. Since haptic encoding typically requires serial information acquisition over several seconds, the haptic object processing system should be optimised for storing input over many seconds. Haptic object recognition may therefore be less sensitive to manipulations of temporal delay than is vision. This was tested in two sequential object matching studies which varied inter-stimulus interval (ISI).

3.1.1 Effects of ISI on tactile and haptic processing

A small number of studies have examined haptic object matching at different ISIs. The results of these studies have been mixed, and are not fully consistent with evidence from studies of tactile/haptic working and short-term memory with simpler stimuli. As yet, no clear explanation has emerged as to why these discrepancies may have occurred. We first review evidence from four studies of tactile/haptic working and short-term memory which did not specifically examine object matching before summarising the results of five haptic object matching experiments.

Gilson and Baddeley (1969) and Sullivan and Turvey (1972) examined recall of the location of a tactile stimulus applied to the underside of the forearm after delays ranging from 0s to 60s. In both studies, participants either remained quiet or performed a simple arithmetic task during the delay period. The arithmetic task functioned as articulatory suppression to prevent verbal rehearsal. Errors increased as a function of delay and after articulatory suppression in both studies. Gilson and Baddeley found that articulatory suppression only impaired recall at delays of over 10s, whereas Sullivan and Turvey found that articulatory suppression impaired recall independently of delay. Gilson and Baddeley found that errors were still increasing after 60s delays in the quiet condition but reached asymptote after 45s in the articulatory suppression condition, whereas Sullivan and Turvey found that errors in both conditions reached asymptote after 5s. Gilson and Baddeley argued that there were two distinct processes involved in tactile short-term memory: a sensory after-image which persists for approximately 10s after initial presentation and is not susceptible to articulatory suppression, and a more abstract, higher-order process requiring rehearsal, which is impaired by articulatory suppression but is not necessarily verbal. In contrast, and consistent with their results, Sullivan and Turvey concluded that tactile memory could be explained solely by the decay of an initial sensory trace.

Miles and Borthwick (1996) repeated Gilson and Baddeley's (1969) experiment, and did not replicate the interaction. Similar to Sullivan and Turvey (1972), they found that increasing delays and concurrent articulatory suppression increased errors independently. Furthermore, they found that different articulatory suppression tasks and tactile interference – running a pen back and forth over the possible stimulus locations during the delay period – impaired recall equally. However, unlike Sullivan and Turvey, Miles and Borthwick found that errors were still increasing after delays of 20s. Miles and Borthwick argued that their results supported the existence of a decaying sensory trace but not of a separate, abstract process. They also argued that the detrimental effects of articulatory suppression were due to a general reduction in the availability of a central processing resource. Thus, a higher cognitive load made the location harder to memorise, rather than articulatory suppression interfering specifically with a verbal rehearsal mechanism.

These three studies used similar tasks with a single tactile stimulus applied to the arm. More recently, Gallace, Tan, Haggard and Spence (2008) investigated memory for tactile stimuli applied to multiple locations on the body simultaneously. Participants reported whether one of up to six vibrotactile stimuli had been presented to a body location indicated by a post-stimulus visual probe. As in the previous studies, Gallace et al. found that errors increased as the delay between the stimulus and the probe lengthened. Furthermore, errors increased more rapidly as the number of stimuli increased, suggesting that the capacity of tactile memory may be fairly limited.

The four studies described thus far support the existence of transient, tactile sensory memory since all reported worse recall at greater delays. However, all tested the ability to spatially locate simple, passively perceived single touches. Furthermore, the nature of any tactile memory used by participants in these studies is unclear. It is unclear what these results imply for the haptic recognition and matching of more complex, 3D stimuli which are actively explored.

We now review four studies that have examined haptic 3D shape matching over varying delays and then three haptic spatial matching studies which have manipulated ISI. Millar (1974) compared the performance of sighted and blind children on a haptic matching task using novel shapes and delays from 5s to 30s, and found that errors and reaction times increased linearly as delay increased. Kiphart et al. (1992) examined matching of objects constructed from LEGO blocks. Performance was equally good after ISIs of 5s and 15s but was much worse after a 30s ISI, with no further decline after 45s. Both of these results are consistent with a decline in performance over time, consistent with the tactile memory studies discussed above. Kiphart et al. argued that this performance was unlike that seen in other modalities, indicating a unique, haptic short-term memory process.

Woods, O'Modhrain and Newell (2004) compared visual, haptic, and crossmodal visual-haptic and haptic-visual matching across delays from 0s to 30s using a set of L-shaped stimuli which varied parametrically along their vertical and horizontal axes. They found that both visual and haptic matching worsened from 0s to 15s but with no further decline after 30s. Crossmodal matching, however, remained stable from 0s to 15s but declined after 30s. However, the overall pattern in both unimodal and crossmodal conditions was consistent with a general decline in performance as ISI increased, even where this decline was not statistically significant. Furthermore, there was no interaction between modality and ISI for either unimodal or crossmodal matching, indicating that the same process could account for results in both modalities, and that, contrary to Kiphart et al.'s suggestion, haptic short-term memory is not unique.

Norman, Clayton, Norman and Crabtree (2008) found contrasting results with a sequential matching task using more naturally shaped objects – plastic moulds of bell peppers. There were four modality conditions: haptic-haptic, visual-visual, haptic-visual and visual-haptic matching. During visual presentations, the objects were rotated in depth about their vertical axis to attempt to match the exploratory movements of the hands to all sides of the object. Hit rates actually improved as ISI increased from 3s to 9s to 15s. Furthermore response bias declined as ISI increased: after 3s, participants were strongly biased to respond "same" but this bias was almost eliminated after 15s. The effects of modality and ISI did not interact. Norman et al. (2008) argued that longer ISIs facilitated the encoding and consolidation of memory for object shape. Thus, Norman et al. (2008) and Woods et al. (2004) both found a similar pattern of results for unimodal vision, unimodal haptics and for crossmodal matching, suggesting that the two modalities may use similar processes and representations for object recognition. However, in contrast to all the studies reviewed so far, Norman et al. reported an improvement in performance at longer ISIs.

Consistent with the findings of Norman et al. (2008), Zuidhoek et al. (2003) found that performance on a haptic orientation matching task was better after a delay of 10s than after no delay. Blindfolded participants first explored a reference bar with one hand, then rotated a second, test bar with the other hand until they felt the two bars to be parallel. Participants made smaller errors after a 10s delay than after no delay, and this effect was larger when the bars were placed further from each other. Zuidhoek et al. (2003) interpreted this as a shift over time from an egocentric, body-centred reference frame to an allocentric, external reference frame, resulting in more veridical encoding of the physical orientation of the bars in relation to each other after longer delays.

Kaas, van Mier, and Goebel (2007) used fMRI to examine the neural networks involved in a task similar to that used by Zuidhoek et al. Participants matched the orientations of reference and test bars after delays ranging from 0.5s to 10s. ISI did not influence behavioural performance, but there was a shift in the neural loci of activation. Activation in primary somatosensory cortex was observed in the first 2-4s after exploration of the reference bar and during matching. Activation then shifted from somatosensory cortex to prefrontal areas and parieto-occipital cortex 4-6s after exploration of the reference bar. Kaas et al. argued that this indicated a shift from a sensorimotor representation to the maintenance of a more cognitive, haptic-spatial representation. Such a shift is consistent with the hypothesis of a shift from egocentric to allocentric reference frames over time.

Finally, Voisin, Michaud, and Chapman (2005) examined the contribution of different frames of reference to haptic discrimination of simple 2D angles for ISIs from 5s to 15s. Participants used their right index finger to judge which of two sequentially presented 2D angles was greater. The angles were both presented either 30° or 60° to the right of the participants' midsagittal plane. Performance was broadly similar at both ISIs, but for stimuli scanned further to the side of the participant accuracy improved after 15s delays. These results were consistent with those of Zuidhoek et al. (2003), supporting the initial use of an egocentric reference frame in haptic perception followed by a slow recoding to an allocentric reference frame.

The studies reviewed above used a range of methodologies and present somewhat mixed evidence. Nevertheless there appears to be an important distinction between those experiments examining passive, tactile performance and those examining active, haptic performance. The former studies (Gallace et al., 2008; Gilson & Baddeley, 1969; Miles & Borthwick, 1996; Sullivan & Turvey, 1972) consistently point to a simple tactile sensory trace which decays over time. In contrast, the latter studies have reported performance both deteriorating (Kiphart et al., 1992; Millar, 1974; Woods et al., 2004) and improving (Norman et al., 2008; Voisin et al., 2005; Zuidhoek et al., 2003) during the seconds following haptic exploration. Furthermore, it is not clear whether the results from the object matching tasks (Kiphart et al., 1992; Millar, 1974; Norman et al., 2008; Woods et al., 2004) and the orientation matching tasks (Kaas et al., 2007; Voisin et al., 2005; Zuidhoek et al., 2003) should be combined. Orientation in physical space is irrelevant in the former task but is critical for the latter task. Nevertheless, orientation forms part of haptic object representations. Performance on haptic object recognition tasks suffers when there is a task-irrelevant change of object orientation between study and subsequent recognition (Craddock & Lawson, 2008; Lacey et al., 2007; Lawson, 2009; Newell et al., 2001). However, none of these experiments have examined how orientation interacts with delay in haptic object recognition. The results of the studies described above which compared visual and haptic matching (Norman et al., 2008; Woods et al., 2004) are consistent with performance in both modalities using shared processes and representations. This in turn suggests that there should be similar effects of orientation changes and delay for haptic as for visual object recognition.

3.1.2 Effects of ISI and orientation changes on visual object recognition

Orientation-sensitivity has been the subject of much theoretical debate in visual object recognition research (e.g. Biederman & Gerhardstein, 1993; Lawson, 1999; Tarr & Cheng, 2003). It has also been used as a marker for the use of perceptual representations in object recognition tasks. It is unlikely that semantic or name representation encode orientation, so a reduction in orientation-sensitivity has been taken to indicate a shift away from perceptual representations to more abstract representations. The time-course of this shift has been examined for visual object recognition, and we will now review that research.

Ellis and colleagues (Ellis & Allport, 1986; Ellis, Allport, Humphreys, & Collis, 1989) conducted sequential matching tasks with photographs of familiar objects with ISIs of 0.1s, 0.5s and 2s. Matching time slowed as ISI increased. Furthermore, at the shorter ISIs, matching was faster when objects were shown at the same orientation in depth, while at the 2s ISI there was no such difference. There was no same-orientation advantage at an ISI of

0.5s when the ISI was filled with a visual mask rather than being blank. Finally, in all conditions there was an advantage for different orientation matches over matches between objects with the same name. They argued that their results supported a distinction between three types of representation: An orientation-specific, temporary object representation which dissipates quickly and is disrupted by masking; a more abstract, orientation-independent shape-based object representation which allows matching over orientation changes and is unimpaired by masking; and a semantic or name representation used to match different objects with the same name. These distinctions are similar to those hypothesised to explain the pattern of results observed in the haptic matching studies described above; initially an egocentric, orientation-sensitive sensory representation guides performance but this is supplanted by a more abstract, allocentric representation over time and finally there are non-perceptual semantic and name representations. Note, however, that the ISIs tested (only up to 2s) were much smaller than those used in the haptic matching studies reviewed above.

In a similar study, Lawson and Humphreys (1996) examined the effects of orientation in depth on visual sequential matching of line drawings of familiar objects at short (0.6s) and long (2.5s) ISIs. Matching was faster at short ISIs and there was a greater benefit for same-orientation matching at short compared to long ISIs. They argued that their results demonstrated the use of durable, orientation-specific representations even at longer ISIs, although their effects were diluted over time by the availability of less orientation-specific representations at longer ISIs.

Finally, Humphrey and Lupker (1993) also conducted a picture-matching study with ISIs of 0.1s, 2s, and 5s, but they presented plane-rotated rather than depth-rotated objects. They again found that matching responses slowed as ISI increased, and they found an advantage for matching pictures in the same orientation which persisted at all ISIs, contrary to Ellis and colleagues' (Ellis & Allport, 1986; Ellis et al., 1989) hypothesis that an orientation-invariant representation mediates matching at longer delays. This difference may result from the visual system using different processes to compensate for plane-rotations and depth-rotations (Lawson, Humphreys, & Jolicoeur, 2000).

Thus, the evidence from the visual literature suggests that objects initially activate orientation-dependent perceptual representations but that over time the effects of these may be supplanted by the use of more abstract, orientation-invariant representations. Note too that the maximum ISI tested in any of these studies was only 5s.

3.1.3 Effects of ISI and orientation changes on haptic object recognition

We have reported a same-orientation benefit in a haptic old-new recognition task across delays of around 15min (Craddock & Lawson, 2008) and at short intervals of approximately 5s in a sequential matching task (Lawson, 2009). However, we are not aware of any studies of the orientation-sensitivity of haptic object recognition that have used the same task and stimuli whilst varying ISI. There are two important issues to examine: first, whether ISI influences haptic object recognition and, second, whether any effects of ISI are modulated by orientation-sensitivity.

First, in any modality increasing ISI would usually be predicted to make performance worse since transient representations are no longer available and information must instead be retained by an imperfect memory system. As reviewed above, the results of tactile location tasks (Gallace et al., 2008; Gilson & Baddeley, 1969; Miles & Borthwick, 1996; Sullivan & Turvey, 1972) are consistent with this expectation, as are the findings of some haptic (Kiphart et al., 1992; Millar, 1974; Woods et al., 2004) and visual (Humphrey & Lupker, 1993; Lawson & Humphreys, 1996) object matching studies. Surprisingly, Norman et al. (2008) reported the opposite pattern of results: improved performance at longer ISIs for both haptic and visual object matching of natural shaped 3D stimuli. Furthermore, this unexpected result was consistent with results from haptic angle and orientation matching studies (Voisin et al., 2005; Zuidhoek et al., 2003). The motivation for the present studies was therefore to investigate whether the unexpected result of Norman et al. (2008) could be replicated. We chose to use ISIs of 3s and 15s, the shortest and longest ISIs used by Norman et al. (2008), since all of the experiments reviewed above suggest that time-dependent changes in haptic performance should be observable after 15s.

Second, if haptically explored objects initially activate orientation-sensitive perceptual representations before activating more abstract, less orientation-specific crossmodal, semantic or name representations then the same-orientation benefit that we have previously reported would be expected to weaken as ISI increases. This prediction is consistent with both results from visual object matching studies manipulating orientation in depth (Ellis & Allport, 1986; Ellis et al., 1989; Lawson & Humphreys, 1996). It is also consistent with the shift in haptic processing identified by Kaas et al. (2007), from an egocentric, sensorimotor representation to a more abstract, allocentric representation (see also Voisin et al., 2005; Zuidhoek et al., 2003). The ISIs that we tested were either side of this shift, which occurred between 4s and 10s after initial object exploration, so again a decrease in orientation-sensitivity was predicted at the long ISI.

3.2 Experiment 5

In Experiment 5 participants performed a sequential haptic object matching task with ISIs of 3s and 15s and for pairs of objects presented at either the same orientation or rotated by 90° in depth from each other. Since we were interested in the nature of the perceptual representations used in the task the stimuli used were novel objects which all shared the same basic shape and so were difficult to represent either semantically or verbally.

Although several of the experiments discussed above manipulated ISI between-participants (e.g. Ellis & Allport, 1986; Humphrey & Lupker, 1996; Norman et al., 2008), the majority manipulated ISI within-participants (Kaas et al., 2007; Kiphart et al., 1992; Lawson & Humphreys, 1996; Millar, 1974; Sullivan & Turvey, 1972; Voisin et al., 2005; Woods et al., 2004; Zuidhoek et al., 2003). There is no clear distinction in performance patterns between the two types of design, with a mixture of declines and improvements in performance at longer ISIs. Since between-participant designs can lack statistical power with small sample sizes we manipulated ISI within-participants. Participants received two blocks of trials, one at each ISI. This design allowed first block performance at either the short (3s) or the long (15s) ISI to be compared to the results of Norman et al. (2008) in which ISI was manipulated between-participants. Norman et al. reported the only haptic object matching experiment in which improvements in performance were observed at longer ISIs so this comparison was of particular interest.

Unlike our previous sequential haptic object matching studies (Lawson, 2009), we expected any same-orientation advantage to occur for both matches and mismatches since we used more homogenous stimuli in the present studies. In particular, these objects all shared the same distinctive fronts and backs, see Figure 3.1, so changes in shape were not confusable with changes in orientation.

3.2.1 Method

Participants

Sixty-four participants (50 female) from the University of Liverpool were recruited in return for course credit. In both the blocked and the mixed conditions, 27 participants were right-handed and five left-handed. Ages ranged from 18 to 57 (mean = 21).

Stimuli

Stimuli were 36 3D rigid plastic "mice" – each approximately 12cm long, 7cm wide, and 5cm tall – printed using a Dimension 3D ABS-plastic printer. The mice varied parametrically on two dimensions, a front hole-to-bump (x) and a rear dip-to-ridge (y). There were six levels of each dimension giving a 6 × 6 shape space (see Figure 3.1), with stimuli numbered in ascending order from 1 at the top left (deepest hole and deepest dip, see Figure 3.2a) to 6 at the top right (tallest bump and deepest dip, see Figure 3.2b) to 31 at the bottom left (deepest hole and tallest ridge, see Figure 3.2c) and 36 at the bottom right (tallest bump and tallest ridge, see Figure 3.2d).

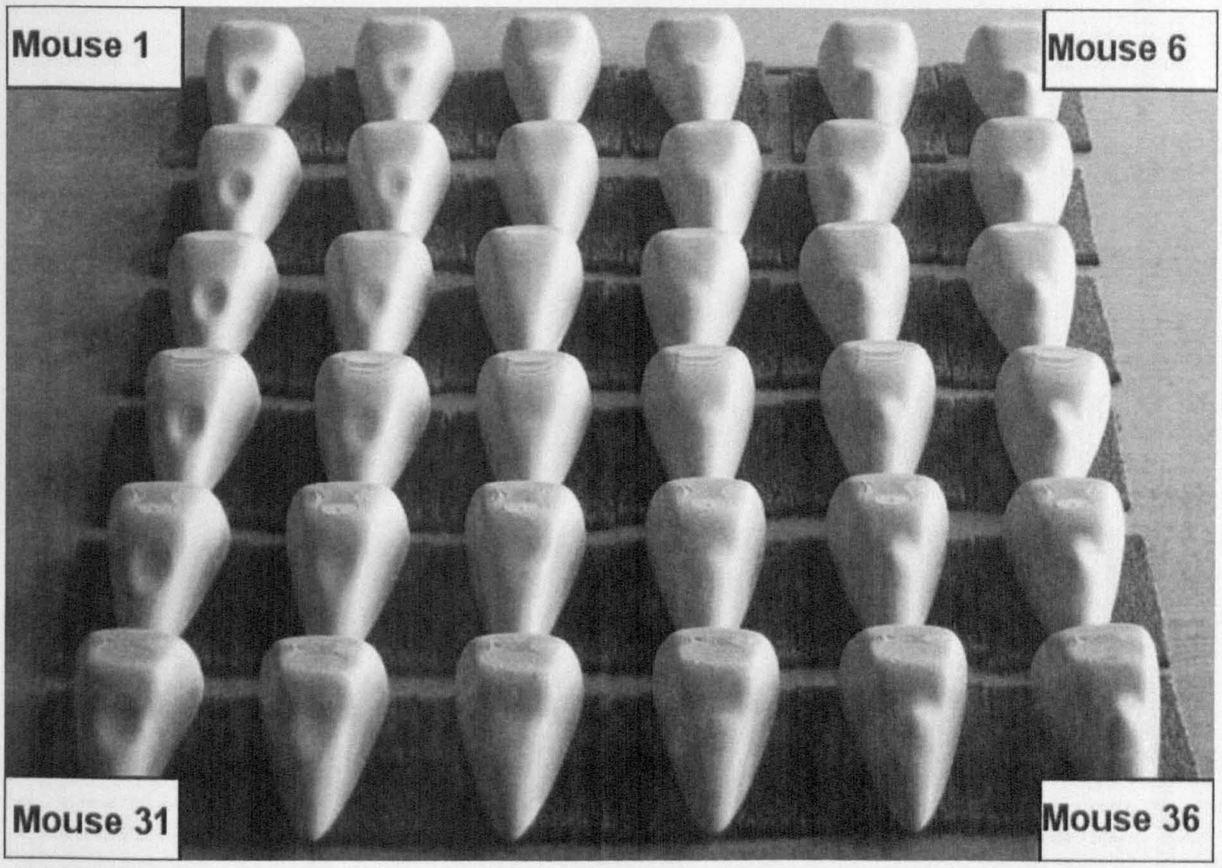

Figure 3.1. The "mice" all facing forward and arranged into their 6 × 6 shape space. The *x*-dimension, which varies the shape of the front of each mouse, runs from the left column (holes) to the right column (bumps) in the figure; the *y*-dimension, which varies the shape of the rear of each mouse, runs from the back row (dips) to the front row (ridges) in the figure.

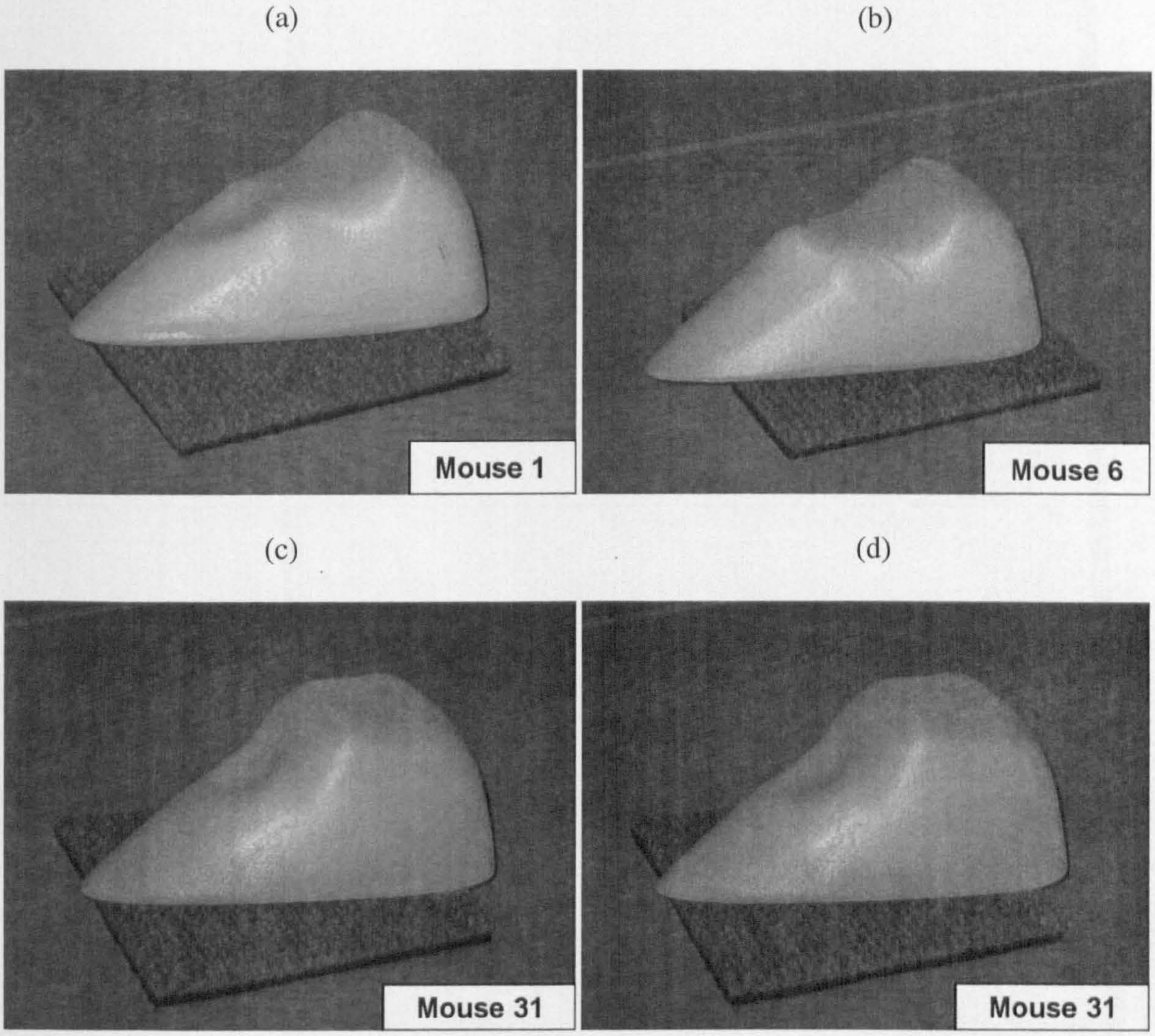

Figure 3.2. Side views of the four mice at each corner of the shape space.

Each mouse was fixed to a 10cm square base made of carpet tile, with its front tip oriented to the middle of one side of the base. The experimenter positioned the mice by placing the base into a 10.5 cm square hole cut into a surround made of a large carpet tile. One side of this hole was marked with green tape and one side with red tape. The front tip of the mouse was aligned with either the green tape or the red tape for green or red orientations respectively, so there was a 90° depth rotation on orientation-change trials, see Figure 3.3.

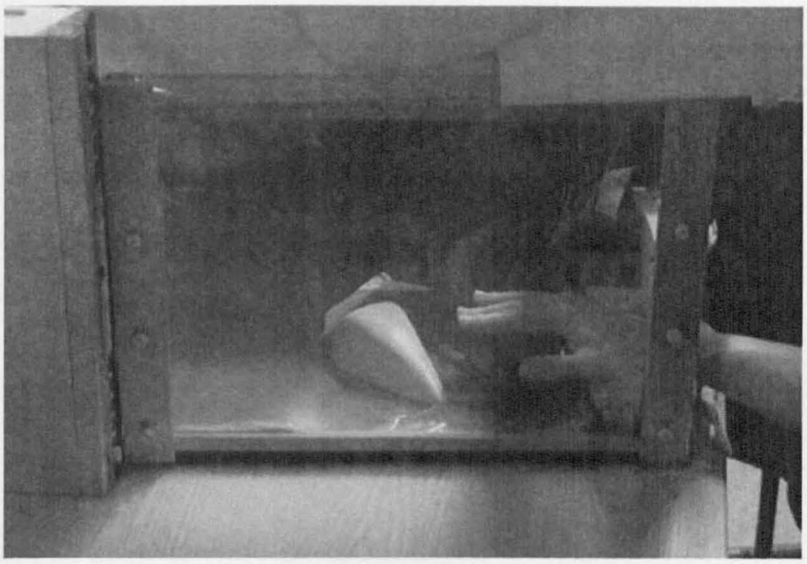

Figure 3.3. Mouse 15 in the red orientation with a participant reaching to touch it with their right hand. The mouse was rotated by 90° anti-clockwise from this position in the green orientation. During the experiment the screen at the front of the apparatus was opaque; participants could not see the mice.

The mouse was hidden from the participant's view by card, a board, and a clouded LCD glass screen. Behind and perpendicular to this glass screen was a 12cm square aperture through which the participant's right hand entered in order to touch the object. An infra-red beam shone across this slot, placed so that it was broken when the participant's hand entered the slot. When this beam was broken a detector sent a signal to the computer controlling the experiment. Participants responded using a button box placed on the table next to their left hand.

Design and Procedure

Trials were presented randomly within a block. Participants in the blocked condition completed a block of 36 short (3s) ISI trials and a block of 36 long (15s) ISI trials. Block order was counterbalanced. Participants in the mixed condition received a single block of 36 short ISI and 36 long ISI trials.

The pairs of mice presented on the 72 trials were identical for all participants, but the orientation of the first mouse and mouse order on mismatches was counterbalanced across participants. For each ISI there were 18 matches (presenting the same mouse twice) and 18 mismatches (presenting two different mice). Within each set, nine trials presented both mice at the same orientation and nine trials presented the second mouse rotated by 90° in depth relative to the first mouse.

All 36 mice were presented on mismatches using 18 *x-dimension* (Table 3.1) and 18 *y-dimension* (Table 3.2) pairings, in which mice differed by two or three steps along the relevant dimension in the shape space. Each mouse was presented four times to each participant: twice on a single match trial when it was presented as both the first and second mouse, and twice as either the first or the second mouse on two separate mismatches.

	x-pairs	
2-step	3-step	2-step
1,3	2,5	4,6
7,9	8,11	10,12
13,15	14,17	16,18
19,21	20,23	22,24
25,27	26,29	28,30
31,33	32,35	34,36

Table 3.1. Mismatch pairs differing on the *x*-dimension (hole/bump).

			y-pairs			
2-step	1,13	2,14	3,15	4,16	5,17	6,18
3-step	7,25	8,26	9,27	10,28	11,29	12,30
2-step	19,31	20,32	21,33	22,34	17,35	24,36

Table 3.2. Mismatch pairs differing on the *y*-dimension (dip/ridge).

Half of the mismatches presented participants with the smaller-numbered mouse first (e.g., 1 then 3) and half presented the mice in the opposite order. This was counterbalanced across participants. Starting orientation was also counterbalanced across participants so that, overall, half of both matches and mismatches presented the first mouse at the green orientation and half presented the first mouse at the red orientation.

On each trial the experimenter positioned the first mouse then triggered a computer to play the words "go now", instructing the participant to move their right hand through the aperture. Five seconds after their hand broke the infra-red beam, the computer played the words "stop now", indicating that the participant should withdraw their hand from the aperture. The experimenter then removed the first mouse and either put it back into the apparatus on matches or replaced it with another mouse on mismatches. Removing then replacing the mouse on matches ensured that the sounds or movements of the experimenter did not allow participants to discriminate matches from mismatches. The computer signalled "go now" either 3s (short ISI) or 15s (long ISI) after the "stop now" signal, indicating that the participant could start to explore the second mouse. Participants decided whether the first and second mice had the same shape and responded with a speeded keypress. A tone provided feedback on accuracy.

Before the start of the experiment, participants were told to ignore the orientation of the mice and were warned that on mismatches the two mice would have very similar shapes. They were shown mouse 1 and mouse 31 visually, and were then given ten haptic practice trials with the same ISI as the first experimental block in the blocked condition or a mix of ISIs in the mixed condition. These trials were easier than the experimental trials because for mismatches the mice were 4-5 steps apart.

3.2.2 Results

In other sequential shape matching experiments, our analyses focussed on matches only (Chapters 5 and 6; see also Craddock & Lawson, 2009a, 2009b; Lawson, 2009) since mismatches typically presented two very different shapes. Manipulations such as size and orientation were therefore only meaningfully interpretable for matches. In contrast, the objects in the current experiment all shared the same global shape and had well-defined fronts and backs, so we expected similar orientation-sensitivity for both matches and mismatches. We therefore chose to follow Norman et al., (2008) in using a signal detection analysis of our results[2].

We calculated *d'* as a bias-free measure of perceptual sensitivity, and *c*, a measure of response bias (MacMillan & Creelman, 2005). We replaced cells in which no errors occurred with a value equivalent to half a hit or false alarm (Schooler & Shiffrin, 2005). We analysed *d'* and *c* with a mixed ANOVA using ISI (short or long) and orientation (same or different) as within-participants factors and condition (blocked or mixed) as a between-participants factor.

One participant was replaced in the blocked condition because she made 39% errors (compared to a mean for the condition of 20%). Four participants were replaced in the mixed condition: two because they claimed to have used the sounds of the experimenter moving the mice during the ISI to respond, one because she made errors on 42% of trials (compared to mean for the condition of 16%), and one because her mean RT was over 7s (condition mean = 3379ms). Thus, in total, five participants were replaced with new participants.

In the blocked condition ($d' = 1.84$, $c = .15$) sensitivity was lower [$F(1,62) = 5.00$, $p = .03$, partial $\eta^2 = .08$] than in the mixed condition ($d' = 2.05$, $c = .09$). There was no difference in bias [$F(1,62) = 1.01$, $p = .3$]. There were no significant interactions involving this factor.

At the short ISI ($d' = 1.97$, $c = .17$) sensitivity was similar [$F(1,62) = .77$, $p = .4$] to

[2] We also performed analyses of RTs and error rates as elsewhere in this thesis. These analyses revealed orientation-sensitivity, with significant speed and accuracy advantages on same-orientation matches.

the long ISI ($d' = 1.91$, $c = .07$) though there was more bias to respond "same" [$F(1,62) = 5.42$, $p = .02$, partial $\eta^2 = .08$]..

On same-orientation trials ($d' = 2.02$, $c = .18$) sensitivity tended to be higher [$F(1,62) = 3.38$, $p = .07$, partial $\eta^2 = .05$] and the bias to respond "same" was greater [$F(1,62) = 12.19$, $p = .001$, partial $\eta^2 = .16$] than on different-orientation trials ($d' = 1.87$, $c = .06$).

Critically, there was no interaction between orientation and ISI for sensitivity [$F(1,62) = .001$, $p > .9$] or bias [$F(1,62) = .08$, $p = .8$], see Figure 3.4.

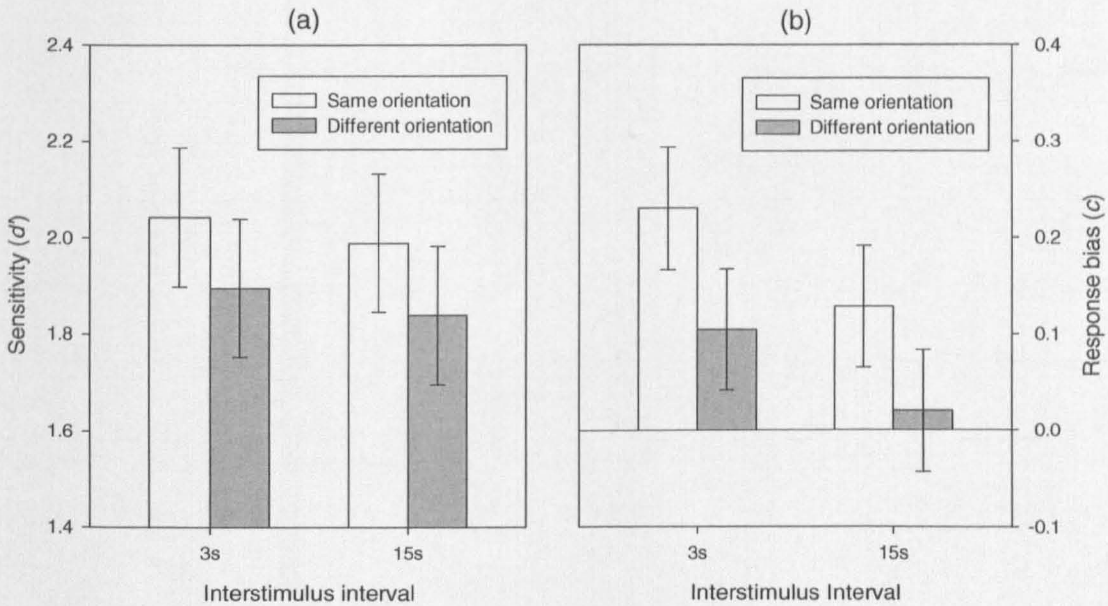

Figure 3.4. Sensitivity (a) and response bias (b) for same-orientation and different-orientation trials at the two ISIs. Error bars represent 95% within-participants confidence intervals calculated using the error term of the ISI × orientation interaction (Loftus & Masson, 1994; Jarmasz & Hollands, 2009).

3.3 Discussion

We found no evidence of a change in sensitivity at the long, 15s ISI compared to the short, 3s ISI, although there was a reduction in response bias. Our results are consistent with those of Kiphart et al. (1992) who found that haptic matching performance was maintained between 5s and 15s. In contrast, Woods et al. (2004) reported that performance declined between 0s and 15s. This difference may be due to superior performance at very short delays being mediated by a transient sensory representation.

Most interestingly, our results do not replicate those of Norman et al. (2008), who had the most similar, naturalistic stimuli to the mice presented in this study. They suggested that people's ability to detect subtle changes in 3D object shape on a haptic matching task improved as ISI increased, based on their finding that hit-rates increased and response bias decreased at 15s compared to 3s ISIs. However, the reduction in bias implies that the improvement in hit rate was offset by an increase in the number of false-alarms, since they reported a significant effect of ISI only on hit-rate, not on sensitivity. Furthermore, we found a similar pattern of results here: our analysis showed that, although there was an increase in the hit-rate at the 15s ISI, there was a similar-sized increase in false alarms and, therefore, sensitivity did not improve. Thus, Norman et al.'s (2008) report of improvements in performance as ISI increased may have been due to a biased performance measure; their results are actually consistent with both our findings and those of Kiphart et al. (1992).

Although we found a trend in the expected direction for higher sensitivity on same-orientation trials, this benefit was not as clear as we have previously observed in similar tasks (e.g., Lawson, 2009). Nevertheless, this trend and the increased bias to respond "same" on same-orientation trials also suggests that orientation was stored. Orientation-sensitivity may have been relatively weak here because the stimuli all had similar global shapes and the same front-back main axis of elongation which clearly defined their orientation. The ease of defining orientation for these stimuli compared to the large, heterogeneous set of models of familiar, nameable objects that we have used elsewhere (Chapters 2, 4, and 5; Lawson, 2009) may have made it easier to learn to compensate for orientation changes within the study.

We found no evidence that the same-orientation benefit weakened at longer ISIs, see Figure 3.4. This was contrary to our predictions based on findings in visual object recognition (Ellis & Allport, 1986; Ellis et al., 1989; Lawson & Humphreys, 1996). Instead, these results suggest that even after a delay of 15s, haptically acquired information about 3D objects is maintained in orientation-sensitive perceptual representations rather than being transferred to more abstract, orientation-invariant semantic or name representations. This is consistent with our finding of long-term maintenance of orientation information for haptically explored familiar objects (Chapter 2) and our suggestion that haptics would maintain initial input with relatively little abstraction for a reasonable period of time. Our results suggest that, when choosing the right key from a bunch by touch, there is no need to rush; but it would be easier if the keys were always pointing in the same direction!

CHAPTER 4| Left and right in haptic object recognition

This chapter is adapted from Craddock, M., & Lawson, R. (2009c). Do left and right matter for the haptic recognition of familiar objects? *Perception*, *38*(9), 1355-1376

4.1 Do left and right matter for haptic recognition of familiar objects?

As demonstrated in Chapters 2 and 3 and elsewhere, haptic object recognition shows similar orientation-dependence to that observed in visual object recognition (Craddock & Lawson, 2008; Lacey et al., 2007; Lawson, 2009; Newell et al., 2001). Changes of orientation constitute a disruptive transformation in perceptual input for both modalities. Nevertheless, one possible source of such variations which is specific to haptics is that that the hands can be moved much more independently than the eyes. For one-handed object exploration, the object must change orientation for the perceptual input derived from one hand to match the perceptual input derived from the other hand. This change in object orientation must be dissociated from more general effects of which hand is used to explore an object (right versus left and dominant versus non-dominant), and the possibility that changes of hand may also constitute disruptive transformations in perceptual input. As discussed below, these manipulations have previously been examined for novel objects, but they have yet to be tested using a more ecologically valid set of familiar objects. The present study investigates whether haptic recognition of familiar objects is influenced by the hand (right or left) used to explore the object on its initial and subsequent presentations, and whether effects of exploration hand interact with the orientation of an object (right or left facing).

4.1.1 The influence of right- versus left-handed exploration on haptic object recognition

Approximately 90% of people report a general preference for the use of the right hand (Annett, 2004; Coren, 1993). Asymmetry of hand performance on a variety of tasks is commonly attributed to hemispheric lateralization. Each hemisphere predominantly receives input from the contralateral side of the body, and thus the right hand predominantly projects to the left hemisphere and vice versa (Hansson & Brismar, 1999). Generally, the left hemisphere is more specialized for language understanding and production, whereas the right hemisphere is more specialized for spatial processing (Corballis, 2003; Gazzaniga, 2000). The literature on lateralization of hand function has been mixed (Millar & Al-Attar 2003; Summers & Lederman, 1990). For example, some studies have shown left hand advantages for naming Braille letters (Hermelin & O'Connor, 1971), while others have found right hand advantages or equal hand performance, or an advantage of using both hands for naming, reading and writing Braille letters (Bradshaw, Nettleton, & Spehr, 1982; Millar, 1984, 1987; Wells-Jensen, Gosche, & Burke, 2008). Heller, Rogers, and Perry (1990) found an advantage for left-hand processing of numbers represented using a vibrotactile display. Heller, Joyner, and Dan-Fodio (1993) compared the susceptibility of the left thumb and right thumb to the haptic horizontal-vertical illusion, and found that illusory effects were only present for the right thumb. O'Boyle, Van Wyhe-Lawler, and Miller (1987) found a left-hand advantage for the recognition of capital letters traced on the palms of the hands. There was a particularly strong advantage when the letters were presented upside-down. The left-hand advantage was annulled by a concurrent spatial memory task but not by a concurrent verbal memory task. All three of these latter studies may be explained by a left-hand, right-hemisphere, spatial processing advantage.

The question of how such hemispheric differences might influence haptic recognition of more complex, 3D stimuli has been relatively neglected. Some studies reported a left-hand advantage when recognising wire shapes (B. Milner & Taylor, 1972; Riege, Metter, & Williams, 1980). However, many of the studies on haptic object recognition do not mention or control for handedness (e.g. Ballesteros et al., 1999; Easton, Srinivas, & Greene, 1997; Klatzky et al., 1985; Klatzky et al., 1987; Lacey & Campbell , 2006; Lacey et al., 2007; Lederman & Klatzky, 1987; Reales & Ballesteros, 1999), or permitted bimanual exploration (Chapters 2 and 5; see also Craddock & Lawson, 2008; Craddock & Lawson, 2009a; Newell et al., 2001). Furthermore, those studies which do specify a single exploration hand typically restricted participants to the use of their dominant hand or their right hand, and did not compare performance between hands (e.g. Amedi et al., 2001; Cooke et al., 2007; Lawson, 2009; Miquée et al., 2008). There were a range of good methodological reasons why the studies listed in this section restricted their testing to a single hand or to the dominant hand. Notwithstanding this, it remains the case that few haptic studies have directly compared right and left hand performance on tasks involving 3D objects.

The findings of the few studies that have compared performance between hands have been mixed. Summers and Lederman (1990) found no evidence for lateralization using a task in which two novel, block objects were explored simultaneously, one in each hand. Participants were instructed either to represent these objects using mental images or verbal descriptions. In the mental image condition, they also drew the objects, while in the verbal condition the object descriptions were tape-recorded. They then attempted to match the drawing or description to one of three haptically presented objects. The same hand explored a given object initially and during matching. There were no overall hand effects, and only weak hand and task interactions were found. Effects of hand changes were not tested.

Fagot and colleagues conducted a series of experiments examining laterality using novel objects composed of coplanar cubes (Fagot, Hopkins, & Vauclair, 1993; Fagot, Lacreuse, & Vauclair, 1993, 1994). Fagot, Hopkins, and Vauclair (1993) had participants explore pairs of objects simultaneously, one in each hand. Subsequent recognition was best when the target shape was explored using the left hand rather than the right, irrespective of the hand with which it was initially explored. Fagot, Lacreuse, and Vauclair (1993) had participants explore an object with either the right or the left hand and then match this object to a visually presented outline drawing. There was no hand-specific recognition advantage, though participants typically explored more of each object at once with the left hand. Finally, Fagot et al. (1994) used a same-different matching task in which an object was explored by either the right or the left hand and then a second object was explored using either the same hand or the other hand. Recognition accuracy was better when the objects were explored with the same hand. There was also a trend for greater accuracy when the second object was explored using the left hand. Furthermore, the right hand spent more time on individual regions of the objects whereas the left hand distributed its exploration time more evenly across the whole object. Despite the differences in the results, all three experiments by Fagot and colleagues suggest that there is some specificity in the exploration strategies employed by each hand (Lederman & Klatzky, 1987, 1990), whereas the study by Summers and Lederman (1990) found no overall effect of handedness on haptic object recognition. However, Fagot and colleagues only tested right-handed participants, and thus it is unclear whether any differences they found could be attributed to handedness per se. Furthermore, the costs of hand changes observed by Fagot et al. (1994) could also be due to a cost associated with the transfer of perceptual information across hemispheres rather than only differences in exploratory hand movements.

Some research has examined differences between hands on discrimination tasks with simpler stimuli. Kappers and Koenderink (1996) compared unimanual and bimanual discrimination of curved surfaces. Performance was better when comparing objects unimanually, and there was no difference in performance between the left and right hands. Thus, while each hand was equally capable of discriminating curvature, comparison across hands suffered. One possibility is that the representation of object curvature may differ for each hand. Another is that there is a cost associated with the transfer of these representations across hemispheres. Similarly, Nefs, Kappers, and Koenderink (2005) found that discrimination of sequentially explored sinusoidal gratings was better with the same hand than discrimination using different hands.

The experiments reviewed above examined recognition of relatively simple, novel objects by the right and left hands. By contrast, the everyday objects that the haptic system can recognise vary much more widely in shape, complexity, texture and so on. In addition, if people preferentially use a given hand to explore objects, they will have more experience of touching those objects with that hand. Thus, it is not clear how these results for simple, novel objects will generalize to the recognition of more complex, familiar objects. We investigated this issue in the two experiments presented here. We hypothesized that people with a right hand preference may be generally better at recognising objects with the right hand through either generally superior manual expertise or, more specifically, greater haptic experience of touching and using everyday, familiar objects. For example, a right-handed person typically holds a pair of scissors with their right hand. The texture and shape of the scissors and the actions associated with them may then be more familiar to the person's right hand than their left hand. Thus, the right-hand preference for most of the population may produce a right-hand advantage that is confined to the recognition of already familiar objects. Additionally, the biomechanics of the hand may render some orientations more amenable to exploration with a given hand. Thus object orientation may directly influence effects of exploration hand on haptic object recognition.

An alternative explanation for a right-hand advantage in haptic object naming would be enhanced access to semantic and linguistic information due to the left-hemisphere specialization for language processing; alternatively, if haptic object naming is predominantly a spatial task, a left-hand, right-hemisphere advantage would be predicted.

In addition, the lateralization of brain function may produce effects of exploration hand on haptic object recognition due to object orientation. Marsolek (1999) proposed that exemplar-abstract and exemplar-specific neural subsystems exist in the left and right hemispheres respectively, and that these subsystems accounted for visual orientation-independence and orientation-dependence respectively. Thus, the left-hand may exhibit greater orientation-dependence than the right-hand if the same neural subsystems are used in haptic object recognition. However, it is unlikely that any differences in hand performance observed here would be attributable to such lateralised systems since the time taken for inter-hemispheric transfer is negligible relative to the typical speed of haptic object recognition, at around 3s.

In the next section we review evidence of how object orientation may influence both visual and haptic object recognition. We then consider how object orientation might interact with exploration hand in haptic object recognition.

4.1.2 The influence of right versus left object orientation on visual and haptic recognition

The orientation-sensitivity of visual object recognition has been the subject of many studies, and the interpretation of the results has led to much debate (e.g. Biederman & Gerhardstein, 1993; Hayward, 2003; Tarr & Bülthoff, 1995; Tarr & Cheng, 2003). Rotations in plane or depth can influence both naming and priming of naming in vision (Lawson, 1999; Lawson & Jolicoeur, 2003; Jolicoeur, 1985, 1990). Furthermore, visually presented objects typically have canonical orientations in which they are recognised best (Palmer et al., 1981). Several researchers have reported that mirror-image reflection does not affect priming of naming but does disrupt recognition tasks (Biederman & Cooper, 1991; Cooper, Schacter, Ballesteros, & Moore, 1992; Srinivas, 1996; Srinivas, Greene, & Easton, 1997). However, Lawson (2004) demonstrated that mirror-image reflection can modulate performance on an implicit task: affective preference was reduced for mirror-reflected as well as depth-rotated pictures of novel objects.

Far less research has investigated the orientation-sensitivity of haptic than of visual object recognition. In Chapter 2 (see also Craddock & Lawson, 2008), we found an effect of initial object orientation in depth on haptic object recognition and costs of depth rotation on an old/new recognition task though not on the priming of naming of haptically presented objects (see also Forti & Humphreys, 2005; Lacey et al., 2007; Lawson, 2009; Newell et al, 2001). As noted earlier, Newell et al. (2001) suggested that orientation-dependence arises in haptics because, due to biomechanical constraints, the fingers mostly explore the rear surface of objects. They found that cross-modal recognition of unfamiliar objects was best when they were rotated by 180° about the y-axis or x-axis between study and test, and thus when front and back surfaces were exchanged. However, Lacey et al. (2007), using similar stimuli and a similar task, did not replicate this finding: they found that cross-modal recognition was orientation-independent. Furthermore, unimodal haptic recognition was disrupted by rotation about any axis, counter to a biomechanical account of haptic orientation-effects.

Representational and biomechanical accounts both lead to the prediction that, for instance, where a left-facing, bilaterally symmetrical object is first explored with one hand, then it must be rotated by 180° to be right-facing to equate the perceptual input when subsequently presenting the object to the other hand. In contrast, such a 180° rotation could disrupt subsequent recognition of that object with the same hand since the hand would experience different surfaces across the two presentations. Thus the effects of object orientation and exploration hand should interact. This could not be examined in the experiments described above because exploration was with both hands.

Several studies have examined effects of mirror reflection on performance of haptic and tactile mental rotation tasks. Performance has generally been found to be similar to that observed in vision (see Prather & Sathian, 2002, for a review). Although several studies have compared performance on haptic tasks between mirror-symmetric and non-mirror-symmetric objects (Jüttner, Müller, & Rentschler, 2006; Rentschler, Osman, & Jüttner, 2009; Rentschler, Jüttner, Osman, Müller, & Caelli, 2004), only one study to date has looked at effects of mirror image reflection per se on haptic object recognition. Srinivas, Greene, and Easton (1997) found that haptic and visual recognition and memory of novel 2D patterns was disrupted by right-left reflection. They explained their results using transfer-appropriate processing: only features of a stimulus that are relevant for the task being performed are encoded. They noted that the identity of a 2D pattern often depends upon its right-left orientation; for example, reflection of the letter *p* produces a different letter, *q*. Thus, right-left orientation would be expected to influence the recognition of 2D patterns. In contrast, they argued that right-left orientation is not informative for identifying most familiar 3D objects – a mirror-image reflection of a car is still a car – and thus that their findings may not generalize to visual and haptic recognition of 3D objects. This was tested in the present experiments.

Right-left orientation is clearly important when grasping objects. One would typically hold a knife by its handle, not its blade, so it is important to locate the handle. However, there is evidence that different neural substrates subserve grasping and recognition, and, accordingly, that the two rely on fundamentally distinct processes (Culham et al., 2003; Goodale, Milner, Jakobson, & Carey, 1991; James et al., 2003; A.D. Milner & Goodale, 2008; Rice, Valyear, Goodale, Milner, & Culham, 2007; Valyear, Culham, Sharif, Westwood, & Goodale, 2006). For example, Humphreys and Riddoch (2001) described a patient who could not select a visually presented object when given its name (e.g. "pick up the cup") or a perceptual description (e.g. "pick up the red object") but who could choose the correct object when told of an action associated with that object (e.g. "pick up the object you can drink from"), while other patients displayed the opposite pattern of performance. If motor processing is distinct from recognition then object recognition might not be influenced by right-left orientation.

Nevertheless, grasping is one of the basic exploratory procedures employed when haptically recognising objects (Lederman & Klatzky, 1990) so grasping might be expected to influence haptic more than visual object recognition. There is evidence that object recognition may influence the programming of grasping movements. For example, Creem and Proffitt (2001) found that participants often grasped objects inappropriately for the use of those objects when simultaneously performing a semantic, word-pair recall task, indicating that some semantic processing is necessary to guide visuomotor interactions with familiar objects. This, in turn, raises the possibility that factors influencing grasping or other object-directed actions may also influence object recognition. In addition, action representations are automatically activated when viewing and naming manipulable objects (e.g. Chao & Martin, 2000; Creem-Regehr & Lee, 2005; Grèzes & Decety, 2002; Grèzes, Tucker, Armony, Ellis, & Passingham, 2003). These representations are associated with the typical use of such objects or are afforded by visual properties such as orientation (Grèzes et al., 2003; Tucker & Ellis, 1998, 2004).

Other studies have examined the reverse interaction: whether motor representations of object-directed actions influence visual object recognition. Bub, Masson, and Bukach (2003) trained participants to associate colours with action-gestures, and then presented coloured familiar objects. The gestures associated with the colours could be congruent or incongruent with the objects. Gestures were produced faster in response to their associated colour when they were congruent with the coloured object, but coloured objects were not named faster if the colour-associated gesture was congruent with the object, suggesting that action representations were not aiding object recognition. However, Helbig, Graf, and Kiefer (2006) pointed out that the colour-gesture associations taught by Bub et al. were arbitrary. Helbig et al. presented pairs of objects sequentially. The second object was named more accurately when the same action was associated with both objects (e.g. dustpan then frying pan, both of which are grasped by the handle), suggesting that priming an action representation can facilitate object recognition. Similarly, Vainio, Symes, Ellis, Tucker, and Ottoboni (2008) reported that categorisation of an object as man-made or natural was more accurate if it was preceded by an animation of a hand performing an appropriate grasp. However, these two results may reflect short-term motor priming and may not generalize to recognition over longer time periods.

These studies provide some evidence that actions and motor representations can affect object recognition, but they have only presented stimuli visually. Furthermore, only Creem and Proffitt (2001) had people grasp real objects. Action and motor representations may be particularly important for the haptic modality, given the importance of proprioceptive and kinaesthetic sensations to object processing by the hand. Furthermore, much of our haptic experience with familiar objects, particularly artefacts, is likely to result from using those objects. For example, we would typically touch a knife only when we wished to cut something. In contrast, we acquire visual experience of many objects with which we never interact. Thus, actions are likely to be more strongly associated to haptic than to visual object representations. The orientation of an object, the actions typically associated with it and the dominant hand of the participant might all be expected to play important roles in haptic object recognition.

Two experiments were conducted to investigate three questions arising from this research. First, is there an advantage to the use of the dominant hand when identifying familiar objects haptically? As outlined above, the dominant hand may benefit from greater manual expertise in general and from more experience with familiar objects, and thus may recognise everyday objects more efficiently. Furthermore some differences may arise due to hemispheric lateralization. In addition, the results of one-handed exploration in Experiments 6 and 7 here can also be compared to those for two-handed exploration in Chapter 2 to examine whether there is any benefit to using two hands rather than one for familiar objects. Second, does the orientation of the object interact with the hand used to explore the object? Acting on objects is important for haptic object recognition, and object orientation often determines the appropriate movement required to act on an object. If objects are easier to recognise when they are oriented to be easily grasped, then the right hand should show an advantage for identifying right oriented objects and the left hand for left oriented objects. Third, how might changes of hand or changes of object orientation influence priming of naming? If different representations are formed by the right and the left hand or for different object orientations and if there is a cost associated with remapping from right to left hand representations or across orientation, then priming might be reduced following hand or orientation changes. Furthermore, these two effects might interact: if orientation-dependence in haptics arises from the biomechanical constraints of the exploring hand, then priming should be greatest when the same surface is explored, regardless of hand. Thus, if exploration hand does not change, priming should be best when orientation does not change; if exploration hand does change, priming should be best if the orientation also changes, since this would cause the same surface to be explored.

4.2 Experiment 6

In the first experiment, right-handed participants named haptically presented objects in two blocks. The objects were placed in right or left orientations. These orientations typically presented the objects in the position most appropriate for grasping by the relevant hand. Thus, for an object with a handle, the right orientation was one in which the handle was nearest to the right hand. The objects were explored with either the right or left hand and both exploration hand and object orientation could change between blocks.

4.2.1 Method

Participants

Thirty-two right-handed students from the University of Liverpool were recruited. Ages ranged from 18 to 29. Different participants were tested in the two experiments reported here.

Stimuli

Forty-eight familiar objects were used, see Appendix II (a full set of photographs of all 48 objects in their "right" orientations is available on the Supplementary CD). Objects were typical examples of manmade, nameable, familiar artefacts from a wide range of categories. They had a diversity of shapes, sizes, textures, and functions. Each object was glued to a 20 cm x 20 cm ceramic tile and assigned a left and a right orientation in relation to the position of the head and trunk of an observer and based on how the object is usually grasped or used. Objects were selected to be bilaterally symmetric such that a 180° rotation in depth produced an approximate mirror-image reflection, see Figure 4.1. Some objects had minor deviations from perfect bilateral symmetry about the vertical plane (e.g. hammer, scissors, and tongs) but performance on these items was consistent with that on other items.

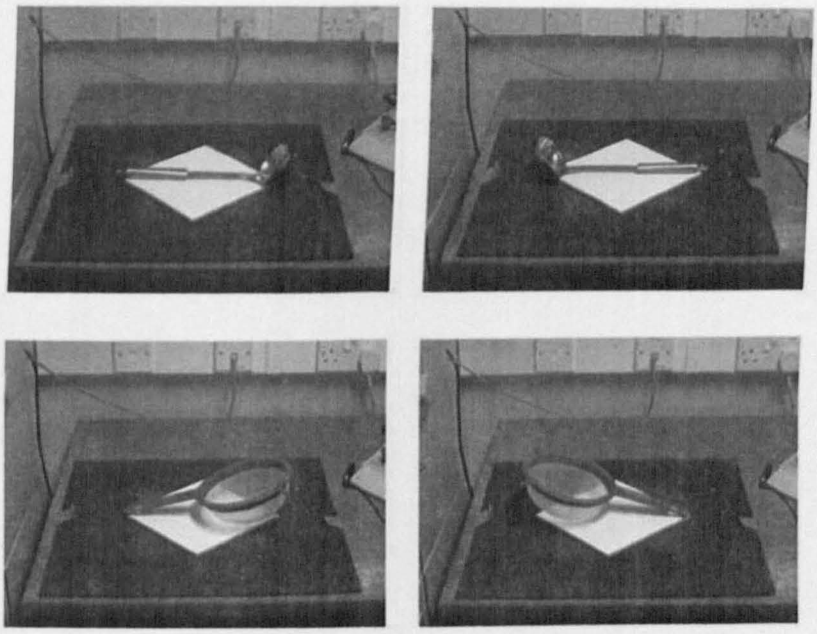

Figure 4.1. Ladle and sieve used in Experiments 6 and 7, shown in their respective left (on the left) and right (on the right) orientations.

Design and Procedure

Participants were given a list of names of the objects that would appear in the experiment and were asked to read them aloud. They were then shown the 50 cm^2 carpet tile on which the objects would be placed and the starting positions in which they should place their hands. These positions were indicated by pieces of masking tape at the centre of the left and right edges of the carpet tile (see Figure 4.1). The tape allowed participants to locate the starting hand positions consistently without vision. Carpet tile was used to muffle sounds made by placing the objects. Participants put on a pair of safety goggles covered in several layers of masking tape and confirmed that they were unable to see the area in which the objects would be placed.

Participants then named each of the 48 objects by touch alone in the prime block and then again in the target block. Each block was divided into two sub-blocks of 24 trials: one block of left hand trials, and one block of right hand trials. The order of presentation of left (L) and right (R) hand sub-blocks was counterbalanced across the prime and target blocks using four orders: LR-LR, LR-RL, RL-LR, and RL-RL. Before each sub-block, the experimenter instructed participants to use either the right or left hand as appropriate, and not to lift or reposition the objects. Participants were given a brief break between the two blocks, and were not informed that objects would be repeated. During the break, the objects were hidden and participants were allowed to remove the goggles.

Objects were allocated to sixteen sets of three (see Appendix II for the set allocation). In the first, prime block, eight of these sets were presented in left object orientations and eight in right object orientations. In the second, target block, four of the sets presented at a given orientation in the prime block were presented in the same orientation; the other four sets were presented in the other orientation. Thus, eight sets were presented at the same orientation in both blocks, and eight were presented at a different orientation in each block. Hand of exploration was also varied. Two of the sets presented in a given object orientation condition (e.g. left orientation in the prime block and right orientation in the target block) were explored with the left hand in the prime block; the other two sets were explored with the right hand. One of each of these two sets was explored with the same hand in the target block whilst the other set was explored with the other hand. In summary, this design fully counterbalanced for four factors, each with two levels: prime block object orientation (right or left), prime block exploration hand (right or left), target block object orientation (same or different relative to the prime block) and target block exploration hand (same or different relative to the prime block).

Participants were allocated to sixteen groups. The object sets assigned to each condition were rotated using a Latin Square design across all the groups such that no two groups received the objects in the same condition (e.g. group 1 was the only group given the three objects in set A in the left object orientation to be explored by the left hand in both experimental blocks). Each set of objects appeared in each of the sixteen conditions an equal number of times. The experimental software package PsyScope 1.2.5 generated the order of presentation of objects within each block and was used to record responses. The order of right and left hand trials was fixed according to the counterbalancing scheme described above; order of presentation of objects within those blocks was randomized.

On each trial the experimenter placed an object in the centre of the carpet tile in the appropriate orientation, and then started each trial once the participant had positioned their exploration hand on the appropriate tape marker. A single, low-pitched warning beep was played, followed by a high-pitched double-beep 1s later to indicate that participants could start to move their hand. Participants were given unlimited time to name each object aloud, but were instructed to do so both quickly and accurately. Each trial ended when participants named the object or declared that they did not know its name. Response times were recorded from the offset of the double beep[3] using a microphone headset attached to a Macintosh computer as a voice key. The experimenter recorded trials on which participants gave an incorrect name or did not know the name of the presented object (naming errors), trials on which the participant either made a noise before their response (such as saying "erm") or the voice key was not activated by their response (voice key errors), and trials on which the participants either started to move too early or used the wrong hand (movement errors).

[3] Note that since response times were recorded from the offset of the double beep, they include time before participants touched the objects. We analyzed video footage from 12 randomly selected trials from each of 10 randomly selected participants, and estimated that the mean time to contact the objects was 685ms (*SD* = 104ms). Thus, a fairly constant increment of around 700ms was added to the overall haptic RTs.

4.2.2 Results

We report below three analyses of our data: effects of right versus left hand and right versus left object orientation in the prime block, effects of right versus left hand and right versus left object orientation in the target block, and same/different hand and object orientation effects on priming from the prime to the target block. Finally, we report a between-experiment analysis contrasting one versus two handed haptic object recognition using data from Chapter 2. The design of each analysis is described separately in each of the following sections. Both by-participants and by-items analyses were conducted throughout. In the by-participants analyses, response times (RTs) and errors were pooled for each participant across the objects that they received in the various exploration hand × object orientation conditions described in each of the following sections. In the by-items analyses, RTs and errors were pooled for each object across participants who received those objects in each of the various exploration hand × object orientation conditions. *F*-values in the by-participants and by-items analyses are reported using subscripts F_p and F_i respectively.

Trials were excluded from the following RT analyses if voice key (4%) or movement (1%), or naming errors (see below) occurred. Trials were also excluded if such errors occurred for the same object in the other block. No participants were excluded from the analyses. Median rather than mean RTs were used since the median is less affected than the mean by the distributional skew often observed in distributions of RTs.

Prime block analysis: Effects of right/left exploration hand and object orientation

Mixed ANOVAs were conducted on the median RTs and mean percentage errors in the prime block with prime block exploration hand (right or left) and prime block object orientation (right or left) as within-participants/items factors. Group was used as a between-participants factor in the by-participants analysis, and object set as a between-items factor in the by-items analysis. Effects involving these latter two counterbalancing factors are not reported.

There was no effect of exploration hand on RTs [$F_p(1,16) = .005, p = .9$; $F_i(1,32) = .150, p = .7$] or errors [$F_p(1,16) = .010, p = .9$; $F_i(1,32) = .006, p = .8$]. All participants were right-handed, but there was no evidence for a right hand advantage for object recognition: performance was similar for objects explored with the right hand (4325ms; 12% errors) and the left hand (4215ms; 12%).

There was also no effect of object orientation on RTs [$F_p(1,16) = .389, p = .5$; $F_i(1,32) = 1.694, p = .2$] or errors [$F_p(1,16) = .061, p = .8$; $F_i(1,32) = .036, p = .9$]. There was no evidence for an advantage for right-oriented objects (4349ms; 12%) over left-oriented objects (4293ms; 12%).

Finally, there was no interaction between exploration hand and object orientation for RTs [$F_p(1,16) = .418, p = .5$; $F_i(1,32) = .107, p = .7$] or errors [$F_p(1,16) = 1.209, p = .3$; $F_i(1,32) = .670, p = .4$]. Mean RTs and errors were similar (around 4300ms and 12% errors) for all combinations of exploration hand and object orientation. In particular, there was no indication that recognition was easier for the right hand for right oriented objects or for the left hand for left oriented objects.

Target block analysis: Effects of right/left exploration hand and object orientation

Analogous ANOVAs were conducted to those for the prime block analysis. There was a main effect of target block exploration hand on RTs [$F_p(1,16) = 4.615, p = .05$; $F_i(1,32) = 3.985, p = .05$] but not on errors [$F_p(1,16) = 1.003, p = .3$; $F_i(1,32) = .800, p = .4$]. As in the prime block there was no evidence for a right hand advantage for the right-handed participants. Instead, unexpectedly, participants named objects about 150ms faster, though no more accurately, with their left hand (3115ms, 6%) than their right hand (3267ms, 7%).

There was no effect of target block object orientation on RTs [$F_p(1,16) = 1.928$, $p = .2$; $F_i(1,32) = 2.833$, $p = .1$] or errors [$F_p(1,16) = .016$, $p = .9$; $F_i(1,32) = .008$, $p = .9$]. There was no evidence for an advantage for right-oriented objects (3143ms, 7%) over left-oriented objects (3240ms, 7%).

There was only a marginally significant interaction between exploration hand and object orientation for RTs [$F_p(1,16) = 4.467$, $p = .05$; $F_i(1,32) = 1.383$, $p = .2$] and no significant interaction for errors [$F_p(1,16) = 2.494$, $p = .1$; $F_i(1,32) = 1.883$, $p = .2$]. Tukey's HSD tests ($\alpha = .05$) revealed that naming left-oriented objects with the right hand was slower (3370ms, 8%) than naming either left-oriented (3109ms, 7%) or right-oriented objects (3121ms, 5%) with the left hand, but no faster than naming right-oriented objects with the right hand (3164ms, 8%). Thus, any effect was weak and was not replicated in the prime block analysis, so further investigation is needed before any strong conclusions can be reached.

Priming analysis: Effects of changes of exploration hand and object orientation

In the priming analysis, naming RTs and percentage errors from each target block trial were subtracted from RTs and errors from the prime block trial for that object to yield the amount of priming of naming. A full factorial analysis using both prime and target block exploration hand (left or right) and object orientation (left or right) would produce 16 conditions, and the number of trials in each condition would then be too low to yield adequate statistical power. Instead, these variables were collapsed into same versus different exploration hand and object orientation, yielding four experimental conditions. Thus, mixed ANOVAs were conducted on the amount of priming of RTs and change in percentage naming errors using target block object orientation (same or different) and target block exploration hand (same or different) as within-participants factors. Group was used as a between-participants factor in the by-participants analysis, and object set was used as a between-items factor in the by-items analysis. Effects involving these latter two counterbalancing factors are not reported.

There was no significant effect of exploration hand on RTs [$F_p(1,16) = .258, p = .6$; $F_i(1,32) = .009, p = .9$] or errors [$F_p(1,16) = 1.260, p = .3$; $F_i(1,32) = .698, p = .4$]. Although there was substantial priming, with naming being over 1s faster in the target block, there was no benefit to using the same hand in both blocks (1231ms faster RTs; 6% decrease in errors) compared to using a different hand in each block (1183ms; 5%).

There was also no significant effect of object orientation on RTs [$F_p(1,16) = .000, p = .9$; $F_i(1,32) = .071, p = .8$] or errors [$F_p(1,16) = .002, p = .9$; $F_i(1,32) = .006, p = .9$]. Naming of objects placed in the same orientation in both blocks was neither faster nor more accurate (1206ms faster RTs; 5% decrease in errors) than naming of objects placed in different orientations in each block (1208ms; 5%).

Finally, there was no interaction between exploration hand and orientation for either the priming of RTs [$F_p(1,16) = 1.128, p = .3$, see Figure 4.2a; $F_i(1,32) = .012, p = .9$] or of errors [$F_p(1,16) = 1.145, p = .3$, see Figure 4.2b; $F_i(1,32) = .382, p = .5$].

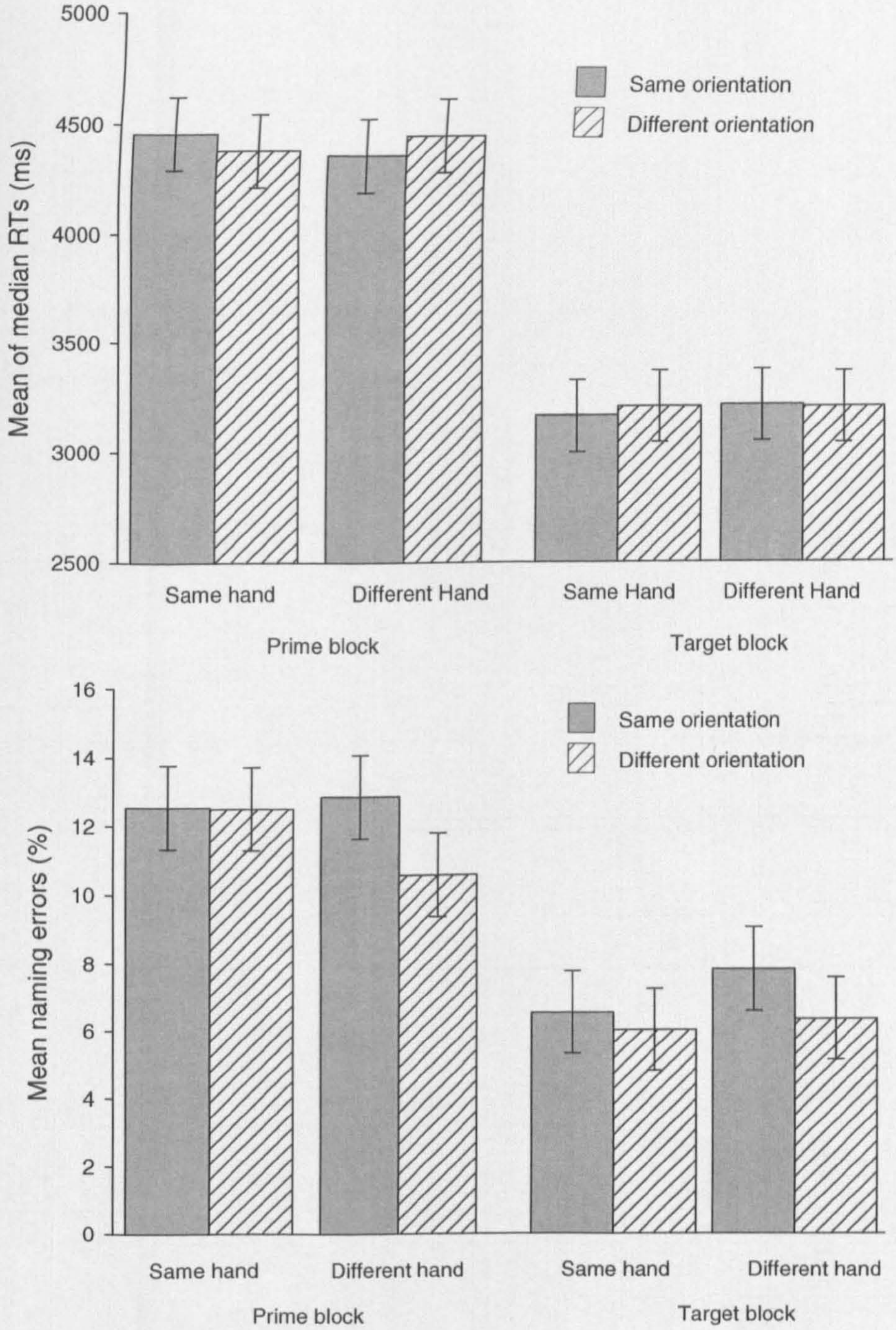

Figure 4.2. Means for (a) median naming RTs and (b) percentage naming errors in prime and target blocks separated by exploration hand and object orientation. Error bars show 95% within-participant confidence-intervals (Loftus & Masson, 1994). Note that "hand" and "orientation" were dummy variables in the prime block.

One handed versus two handed haptic object naming

Twenty-four of the objects presented in Experiment 6 here were also presented (and placed in the same orientation) in Experiment 1 in Chapter 2. This latter experiment used the same procedure as Experiment 6 here, except that the participants used both hands to recognise the objects there. We compared naming RTs and errors for the common orientation of these 24 objects across the two experiments using independent sample t-tests for the by-participants test and matched-pair t-tests for the by-items test. We performed these tests separately for prime block and target block data.

In the prime block, there was a significant effect of the number of exploration hands on errors by-participants (RTs: $t(60) = 1.672, p = .1$; errors: $t(60) = 2.846, p = .006$) and, marginally, by-items ($t(23) = 1.457, p = .08$; $t(23) = 1.662, p = .06$). Naming was marginally slower and significantly less accurate when using one hand (4180ms; 9% errors) than when using both hands (3766ms; 3%). Similarly, in the target block, although there was no effect of the number of exploration hands by-participants ($t(60) = 1.054, p = .3$; errors ($t(60) = .972, p = .3$), there was a significant effect by-items on RTs ($t(23) = 1.822, p = .04$) and, marginally, on errors ($t(23) = 1.488, p = .08$). Again, naming tended to be slower and less accurate when using one hand (3165ms; 5% errors) than when using both hands (2978ms; 4%).

4.2.3 Discussion

First, although all participants in Experiment 6 were right-handed there was no right-hand advantage to haptic object naming - indeed there was a small but significant benefit for left-handed recognition in the target block. There was therefore no evidence that greater manual expertise or increased familiarity with objects produced a dominant hand advantage.

Second, there was no overall effect of object orientation in either the prime or the target block. This contrasts with Chapter 2, in which familiar objects were recognised faster and more accurately in some orientations than in others. This discrepancy in the results may be due to differences in the orientation of the main axis of elongation of the object. A 90° orientation change was used for most of the objects in Chapter 2. For these objects, recognition was faster when the orientation of their main axis of elongation ran right-left rather than front-back relative to the observer. This may have been because less time is needed to make contact when the main axis of elongation of an object runs right-left or because haptic exploration is biomechanically easier for right-left oriented objects. In contrast, bilaterally symmetric objects were presented here in Experiment 6. The 180° rotation in depth between the right and left object orientations produced an approximate mirror image reflection with the main axis of elongation having the same location in both cases, so time to contact and ease of exploration should have been matched for both orientations.

Third, exploration hand and object orientation generally did not interact for either naming itself or priming of naming. Only a weak interaction was found for naming RTs, which was not consistent across blocks. For the right hand in the target block there was some evidence for the predicted interaction between exploration hand and object orientation, with right-oriented objects being somewhat easier to recognise than left-oriented objects. This finding is consistent with Tucker and Ellis (1998) who found that visually presenting objects in an orientation suitable for right-hand grasping conveyed an advantage to right-hand responses when categorising those objects. However, this interaction was weak, was not present in the prime block and did not occur for the left hand. Overall, the results of Experiment 6 provide little evidence of an advantage conveyed by graspable orientations.

Fourth, despite substantial priming of naming from the prime to the target block (see Figure 4.2) neither changes of exploration hand nor changes of object orientation impaired priming of naming. Priming thus transferred efficiently across hands and object orientation.

The former result is not consistent with previous findings of a cost associated with cross-hand transfer of perceptual information (Fagot et al. 1994; Kappers & Koenderink, 1996; Nefs et al., 2005). However, these previous studies presented novel, unfamiliar objects or impoverished, line pattern stimuli. For familiar objects, a number of additional representational factors, such as verbal encoding and semantic priming, can serve to reduce the impact of perceptual factors such as orientation. Nevertheless, such codes can also be employed in the recognition of unfamiliar objects (Lacey & Campbell, 2006). The lack of an effect of orientation changes on priming of naming replicates Experiment 1 of Chapter 2 (see also Craddock & Lawson, 2008) and suggests that naming is relatively insensitive to orientation. The absence of an interaction between exploration hand changes and object orientation changes also suggests that orientation-dependence in haptics may not be caused by biomechanical constraints on hand movements.

Fifth, comparing these results with the studies reported in Chapter 2, there was evidence for superior haptic recognition when using two hands. For example, initial naming using two hands was 414ms faster and 6% more accurate than one-handed exploration. Two hands may convey an even greater advantage for larger objects than those tested here (Wijntjes, Lienen, Verstijnen, & Kappers 2008). Butter and Bjorkland (1976) also found an advantage for two-handed over one-handed exploration of random forms when participants subsequently drew the explored object. Here and in Chapter 2, the objects were presented in fixed orientations and were glued to ceramic tiles so haptic recognition may have been harder than when objects can be freely explored and manipulated. Nevertheless, recognition of these 3D, familiar objects was still similarly accurate to that observed for free exploration (Klatzky et al., 1985) and was much better than recognition of raised line drawings of objects (e.g. Lederman et al., 1990; Loomis et al., 1995).

4.3 Experiment 7

One explanation for the absence of effects on priming in Experiment 6 is that the priming may have been predominantly semantic. If so, then it would not be expected to be influenced by perceptual factors such as object orientation and hand of exploration. However, using similar stimuli and a similar task we demonstrated that a component of haptic priming of naming is specifically perceptual (Chapter 2). In Experiment 3, participants named familiar objects either haptically or visually in a prime block then named all the objects again haptically in a target block. Priming of naming by same-name, different-exemplar photographs of objects was substantial, but was nevertheless significantly reduced relative to priming by haptically presented objects. Thus, although some of the priming we observed in Experiment 6 here may have been semantic, this earlier finding suggests that there was also a substantial perceptual component of priming.

An alternative explanation for the lack of priming effects found in Experiment 6 is that the haptic object representations formed during the initial block contained no information about either exploration hand or object orientation. If there is early and total abstraction from the input stimulus then participants should be unable to remember either of these characteristics. However, if these properties were encoded it would suggest that there is relatively late abstraction from irrelevant stimulus properties in order to achieve haptic object constancy, with this perhaps only occurring at the time of retrieval. In Chapter 2, we found that participants were quite accurate at explicitly detecting whether an object had changed orientation between study and test. However, in Experiment 6 here, objects that changed orientation from the prime to the target block were always rotated by 180° in depth and so were approximately mirror image reflected. Visual memory for which mirror image version was shown is poor (e.g. Lawson, 2004; Seamon & Delgado, 1999), and thus explicitly remembering object orientation here may be harder than in Chapter 2. To test this hypothesis we replicated Experiment 6 with two new tasks replacing naming in the target block: participants in the exploration hand group decided whether a given object had been explored with the same hand or their other hand in the naming block; participants in the object orientation group were asked to decide whether a given object was presented at a different orientation from the naming to the target block.

4.3.1 Method

Participants

Two groups of sixteen participants were recruited in return for course credit or payment, predominantly from the student population of the University of Liverpool. Ages ranged from 14 to 28. All participants except one in the object orientation group were right-handed. Two participants who performed at or below chance in the exploration hand group were replaced. Two participants in the object orientation group were also replaced: one made many naming errors (33%); the other performed at chance in the second part of the experiment.

Stimuli, design and procedure

The same set of 48 objects as used in Experiment 6 was used in Experiment 7. The procedure was similar to that of Experiment 6, except for the following points. First, in the second, target block, the object orientation group decided whether each object was in the same orientation as in the first, naming block; the exploration hand group decided whether they were exploring each object with the same hand as in the naming block. The target block task was only announced immediately before its onset. Second, left hand and right hand trials were not blocked but were interleaved at random. The experimenter told the participant which hand to use for each trial. This change was made to ensure that the exploration hand group could not use order of presentation to help them to determine the correct response in the target block.

4.3.2 Results

A one-sample t-test against chance (50% errors) showed that overall target block performance was significantly above chance when remembering both exploration hand (34% errors; $t(15) = -8.085, p < .001$) and object orientation (23% errors; $t(15) = -8.998, p < .001$). People had often coded which hand they had used to initially explore an object and the orientation of that object in the naming block even though they were not expecting to be tested on either task. The object orientation group performed significantly better than the exploration hand group ($t(30) = 2.878, p = .004$). In Experiment 2 in Chapter 2, participants made only 12% errors when deciding whether an object had changed orientation from study to test. There were several minor differences between this and the present study that preclude direct statistical comparison, but this result is consistent with the present findings in suggesting that more accurate information is stored about object orientation than about exploration hand. We conducted additional analyses for each group separately to determine whether the effects of changes of exploration hand and object orientation interacted.

Remembering object orientation in the target block

Trials on which voice key (3%) or movement errors (1%) occurred in either block were excluded from RT analyses. Repeated measures ANOVAs were conducted on the target block median RTs and mean percentage errors by-participants and by-items for the object orientation group. Exploration hand (same or different) and object orientation (same or different) were within-participants/items factors.

There was a main effect of object orientation for RTs [$F_p(1,15) = 14.315$, $p = .002$; $F_i(1,32) = 6.379$, $p = .017$] and for errors [$F_p(1,15) = 7.614$, $p = .015$; $F_i(1,32) = 33.986$, $p < .001$]. Participants were faster and more accurate when the object was in the same orientation (3549ms; 16%) than in a different orientation (3941ms; 26%). There was a main effect of exploration hand for RTs [$F_p(1,15) = 5.068$, $p = .04$; $F_i(1,32) = 8.250$, $p = .007$] but not for errors [$F_p(1,15) = 1.802$, $p = .2$; $F_i(1,32) = .003$, $p > .9$]. Participants were faster but no more accurate at remembering the original object orientation when the object was explored with the same hand (3627ms, 22% errors) than when the exploration hand switched between blocks (3863ms, 20%). There was no interaction between object orientation and exploration hand for RTs [$F_p(1,15) = 1.726$, $p = .2$; $F_i(1,32) = .158$, $p = .7$] or for errors [$F_p(1,32) = 1.146$, $p = .3$; $F_i(1,32) = 2.608$, $p = .1$], see Figure 4.3.

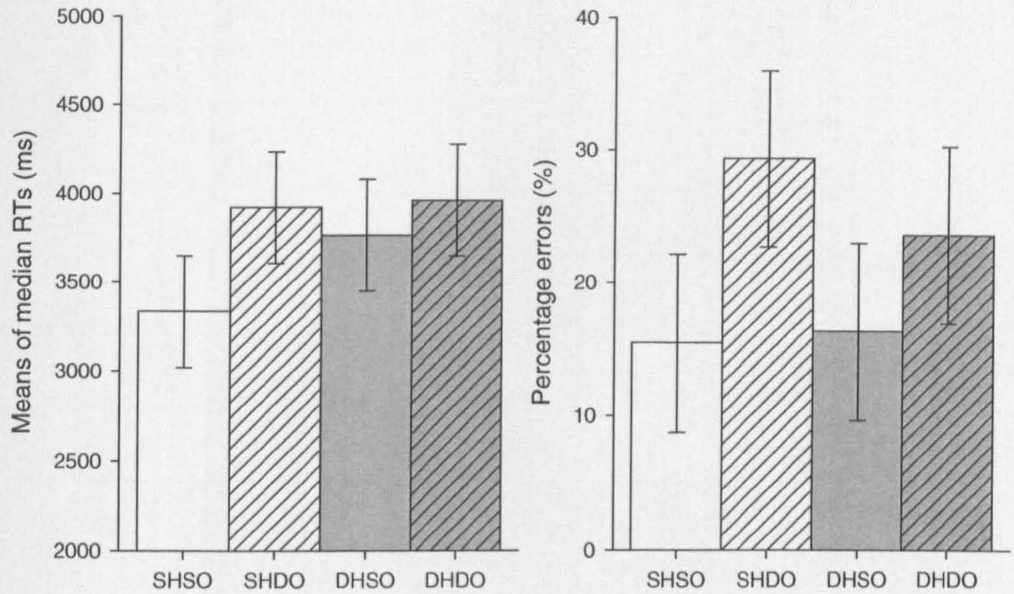

Figure 4.3. Means of median RTs (ms) and mean percentage errors for the object orientation group in Experiment 8. Bars depict data from same hand same orientation (SHSO), same hand different orientation (SHDO), different hand same orientation (DHSO), and different hand different orientation (DHDO) conditions in the target block. White bars depict same hand conditions; grey bars depict different hand conditions. Plain bars depict same object orientation conditions. Hatched bars depict different orientation conditions. Error bars depict 95% within-participant confidence intervals (Loftus & Masson 1994).

Remembering exploration hand in the target block

Trials on which voice key (6%) or movement errors (1%) occurred in either block were excluded from RT analyses. Repeated measures ANOVAs were conducted on the target block median RTs and mean percentage errors by-participants and by-items for the exploration hand group. Exploration hand (same or different) and object orientation (same or different) were within-participants/items factors.

There was no effect of object orientation on RTs [$F_p(1,15) = 2.187, p < .2$; $F_i(1,32) = 2.168, p < .2$] or errors [$F_p(1,15) = .682, p > .4$; $F_i(1,32) = 1.195, p < .3$]. Performance when remembering the original exploration hand was similar if the object was in the same orientation (4396ms; 30%) or a different orientation (4626ms; 34%). There was also no effect of exploration hand on RTs [$F_p(1,15)= .119, p > .7$; $F_i(1,32) = .098, p > .7$] or errors [$F_p(1,15)= .081, p > .7$; $F_i(1,32) = .624, p > .4$]. Performance was similar whether the object was explored with the same hand (4483ms; 31% errors) or the other hand (4538ms; 33%). The interaction of object orientation with exploration hand for RTs was not significant by-participants [$F_p(1,15) = 2.131, p < .2$] but it was by-items [$F_i(1,32) = 5.247, p < .03$] and for errors [$F_p(1,15) = 38.550, p < .001$; $F_i(1,32) = 44.882, p < .001$], see Figure 4.4. Post-hoc Tukey's HSD comparisons using $\alpha = .05$ revealed that participants were similarly accurate when both exploration hand and object orientation were the same (SHSO: 4234ms; 18%) as when both were different (DHDO: 4519ms; 23%). In contrast, they were less accurate if object orientation but not exploration hand changed (SHDO: 4733ms; 45%) or if the exploration hand but not object orientation changed (DHSO: 4558ms; 42%).

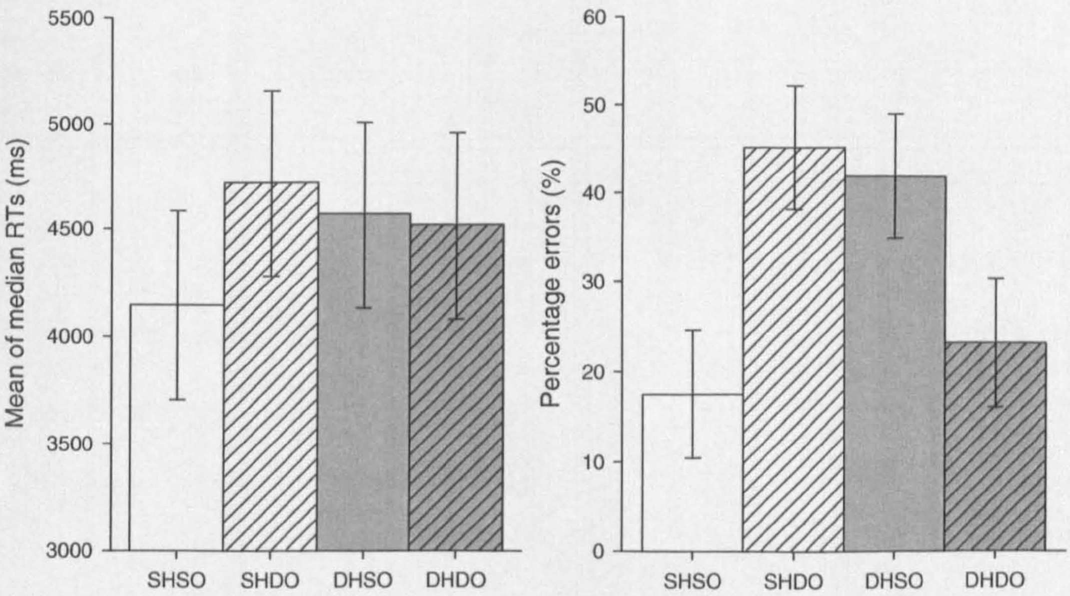

Figure 4.4. Means of median RTs (ms) and mean percentage errors for the exploration hand group in Experiment 8. Bars depict data from same hand same orientation (SHSO), same hand different orientation (SHDO), different hand same orientation (DHSO), and different hand different orientation (DHDO) conditions in the target block. White bars depict same hand conditions; grey bars depict different hand conditions. Plain bars depict same orientation conditions. Hatched bars depict different orientation conditions. Error bars depict 95% within-participant confidence intervals (Loftus & Masson, 1994).

Effects of exploration hand and object orientation on initial naming

Although the naming block was not the critical block in Experiment 7, we analyzed its data for comparison to Experiment 6. The naming block was identical for both groups, so their data was combined. This naming block was also identical to that of Experiment 6 except that left and right hand trials were blocked in Experiment 6 but were interleaved in Experiment 7. Mixed ANOVAs were conducted on median naming RTs and mean percentage errors. Exploration hand (left and right) and object orientation (left and right) were used as within-participants factors. Group was used as a between-participants factor.

There was no effect of exploration hand on RTs [$F_p(1,30) = .407, p = .5$; $F_i(1,32) = .043, p = .8$] or errors [$F_p(1,30) = 1.662, p = .2$; $F_i(1,32) = 2.917, p = .1$]. Participants were neither faster nor more accurate with the right hand (4513ms; 8% errors) than the left hand (4414ms; 10%). There was no effect of object orientation on RTs [$F_p(1,30) = 1.030, p = .3$; $F_i(1,32) = .624, p = .4$] or errors [$F_p(1,30) = .094, p = .8$; $F_i(1,32) = .119, p = .7$]. Participants were neither faster nor more accurate if the object was in a right orientation (4562ms; 8%) than if it was in a left orientation (4365ms; 9%). There was no interaction between exploration hand and object orientation for RTs by-participants [$F_p(1,30) = 2.038$, $p = .2$], but there was by-items [$F_i(1,32) = 19.298$, $p < .001$]. There was no significant interaction for errors [$F_p(1,30) = .001$, $p > .9$; $F_i(1,32) = .004$, $p > .9$]. The significant interaction for RTs by-items was neither in the expected direction nor consistent with Experiment 6, so will not be discussed further. However, the means are reported here for completeness: LHLO (4685ms; 10% errors); LHRO (4340ms; 9%); RHLO (4250ms; 7%); RHRO (4827ms, 7%).

4.3.3 Discussion

The main finding from Experiment 7 was that participants could remember an object's initial orientation and, less accurately, the hand with which they first explored that object in an unexpected memory test. These findings suggest that abstraction away from perceptual factors occurs relatively late in haptic processing since object orientation and exploration hand appear to be coded in long-term haptic representations even when participants are not warned that this information is task-relevant. These results contrast to those from the name priming task used in Experiment 6 in which neither object orientation changes nor exploration hand changes influenced priming.

The object orientation group was influenced by both exploration hand and object orientation. They were faster and more accurate when the object was in the same orientation at both presentations. This influence of object orientation extended Srinivas et al.'s (1997) findings to real, familiar 3D objects. In Experiment 7, neither group knew that they would be required to remember the object's orientation until after they had finished naming the objects in the first block. These results are contrary to Srinivas et al.'s hypothesis that right-left orientation is only encoded when it is relevant to the task. This group also responded faster when exploring the object with the same hand in both blocks, consistent with our suggestion that hand changes may incur a cost to haptic processing and previous evidence of a cost of transfer across hands in other matching tasks (Nefs et al., 2005).

The exploration hand group performed best when both hand and orientation changed or when neither changed. This might have resulted from a bias to respond that exploration hand had changed when participants detected changes of object orientation. This bias would increase accuracy on different-hand different-orientation trials but reduce accuracy on same-hand different-orientation trials. Conversely, if participants did not detect a change to the object orientation they may have been biased to say "same exploration hand", increasing accuracy on same-hand same-orientation trials but decreasing accuracy on different-hand same-orientation trials. This hypothesis is plausible since the superior performance of the object orientation group suggests that object orientation changes were more salient than exploration hand changes.

4.4 General Discussion

Neither exploration hand nor object orientation affected initial naming in either Experiment 6 or Experiment 7, though two hands seem to be more effective than a single hand for haptic object recognition. Neither changes of exploration hand nor changes of object orientation affected priming of haptic naming in Experiment 6. However, both initial exploration hand and initial object orientation were encoded, since participants were able to recall these factors in an unexpected memory task in Experiment 7. Together the results of these two experiments suggest that the haptic object processing system efficiently generalises across both hand of exploration and right versus left mirror images of an object in order to achieve object constancy when naming familiar objects.

The right-handed participants tested did not reveal a right-hand advantage in naming familiar objects, despite the greater experience of the preferred hand in handling objects and its greater manual expertise (e.g. Nalçaci, Kalaycioğlu, Çiçek, & Genç, 2001; Triggs, Calvanio, Levine, Heaton, & Heilman, 2000). As noted earlier, previous observations of right versus left hand advantages have provided mixed evidence that is often highly task-specific (Millar & Al-Attar, 2003; Summers & Lederman, 1990). Our results indicate that haptic naming of familiar objects is not a task on which such advantages occur. Since naming objects haptically requires both linguistic and spatial processing, for which the left and right hemispheres are specialized respectively, the strengths of each hemisphere may cancel each other out in this task. Spatial and manual expertise effects may be easier to detect in the recognition of unfamiliar objects.

Exploration hand also did not interact with object orientation in the predicted direction. In particular, right handed recognition was not superior for right-oriented objects and left-handed recognition was not better for left-oriented objects. This suggests that for haptic object naming there is no benefit of orienting an object so that it can be grasped in the normal way. This is consistent with evidence that recognition and grasping are subserved by different mechanisms (James et al., 2003; Rice et al., 2007; Valyear et al., 2006). Note, however, that in the present experiments participants did not grasp the objects for use and could not pick up the objects. Interactions between exploration hand and object orientation might occur if objects were manipulated as they are in everyday life.

In Experiment 6, priming of naming of haptically explored familiar objects was unaffected by changes of exploration hand or changes of object orientation, replicating and extending Chapter 2's results (and, thus, Craddock & Lawson, 2008). This suggests that the action priming observed in a visual naming task by Helbig et al. (2006) may reflect relatively short-term motor priming rather than object-specific priming. Experiment 7 demonstrated that participants were quite accurate at remembering which hand they had originally used to name each object and the object's original orientation in an unexpected memory task. Thus, the null effects observed in Experiment 6 were not due to a failure to encode exploration hand or object orientation, but may instead be due to task differences. Naming is a relatively insensitive task in comparison to more explicit memory tasks such as old/new recognition (Buchner & Brandt, 2003; Buchner & Wippich, 2000; Meier & Perrig, 2000). Implicit tasks are often relatively unreliable and thus lack statistical power in comparison to explicit tasks. Furthermore, as noted above, for familiar objects a number of representational strategies may be employed that may reduce sensitivity to object orientation or exploration hand. For example, Lacey and Campbell (2006) found that haptic recognition of both familiar and unfamiliar objects was impaired by a verbal interference task at time of recall. This result suggests that haptic recognition relies strongly on verbal representations, which are orientation-independent, reducing the likelihood that effects due to orientation-dependent perceptual representations could be detected. Nevertheless, we have elsewhere demonstrated that there is a perceptual component of haptic priming (Chapter 2, Craddock and Lawson 2008), and that orientation-sensitivity emerges even for familiar objects (Lawson, 2009). Note also that Lacey and Campbell's findings were for crossmodal memory (haptic recognition following visual encoding). Perceptual representations may play a more important role in unimodal tasks such as those reported here.

There is now increasing evidence that haptic object recognition bears broad similarities to visual object recognition in the achievement of object constancy, displaying costs of generalizing across orientation changes (e.g. Chapter 2, Craddock & Lawson, 2008; Lacey et al., 2007; Newell et al., 2001) and size changes (Chapter 5 and 6, Craddock & Lawson, 2009a, 2009b). In the present study we have shown that right versus left mirror image object orientation is encoded in haptic object representations, but that, as in vision, haptic naming is relatively insensitive to mirror image reflection. These similarities are consistent with evidence from imaging studies that the haptic and visual object recognition systems share some neural substrates (Amedi et al., 2001; Amedi et al., 2002; Amedi, et al. 2005) and with behavioural evidence of efficient crossmodal transfer in object processing (Lawson, 2009; Reales & Ballesteros, 1999). We have shown here that haptic recognition of familiar objects generalizes across exploration hands, and that there is no advantage to the use of the dominant hand when recognising familiar objects. Thus, we have demonstrated that the haptic system achieves object constancy across input variation that is specific to the haptic modality; as the visual system readily transfers object information between the right and left visual fields, so the haptic system can easily recognise an object felt with one hand after it has been felt with the other.

PART II| Generalization over size changes

In Part I, the focus was on effects of orientation changes on haptic recognition. The similarities between orientation-sensitivity for haptic and visual object recognition provide preliminary evidence that the two modalities may use similar strategies to attain object constancy. Such effects were demonstrated using sequential shape matching and old/new recognition. Visual and haptic object recognition may involve independent processing routes, but may also converge on a single recognition system, and use the same processes to analyse some properties – in this case, 3D shape. Thus, with some modification, both the *image-mediation* and the *direct-apprehension* models of haptic object recognition may hold true (Lederman & Klatzky, 1987). *Image-mediation* may represent one end of a continuum where the haptic system is forced to use predominantly visual mechanisms, particularly for unusual stimuli such as 2D raised-line pictures (Lederman et al., 1990). *Direct-apprehension* may represent the other extreme, at which purely haptic mechanisms are used. Everyday haptic object recognition may use both mechanisms.

A notable absence – with the exception of Experiment 3 in Chapter 2 – is examination of crossmodal, visuo-haptic performance. This was largely due to a lack of haptic studies using familiar objects both on effects of orientation changes and on the influence of handedness. Thus, the focus was on demonstrating orientation-effects in haptics using a much broader, more ecologically valid range of stimuli than those which had been used in the literature previously, such as Newell et al.'s LEGO blocks (2001), and investigating some potential haptic-specific influences on object recognition.

However, it is important to examine how the haptic system copes with other transformations. For example, the visual system has consistently demonstrated size constancy in object recognition (e.g. Biederman & Cooper, 1992; Furmanski & Engel, 2000). If the haptic system processes size in the same way as the visual system, then it too may demonstrate size-invariance in object recognition. Only Srinivas, Greene, and Easton (1997) have addressed this question, providing evidence that the haptic system does not process size in the same way as vision for 2D patterns. However, this has not been tested with real, 3D objects, for which the haptic system is better suited (Klatzky et al. 1987).

A second reason for this change in focus is that it is relatively difficult to equate orientation across vision and haptics. As will be discussed in the following Chapters, the literature on the effects of orientation changes on crossmodal visuo-haptic recognition has presented a resoundingly mixed picture. It is not clear how well related haptic and visual "views" are. For example, with the caveat that both modalities use a reference frame which is in some sense viewer-centred rather than object-centred, it is not clear that the two modalities use the same reference frame for defining object orientation.

With these issues in mind, a second candidate for assessing crossmodal, visuo-haptic performance was found: effects of size changes. In itself, the topic had received no attention in the haptic literature, and provided a useful alternative method to study the sharing of representations between vision and haptics. Thus, the second part of this thesis will centre on effects of size changes in unimodal and crossmodal settings.

CHAPTER 5| Effects of size changes for real familiar objects

This chapter is adapted from Craddock, M. & Lawson, R. (2009a). The effects of size changes on haptic object recognition. *Attention, Perception, & Psychophysics, 71*(4), 910-923

5.1 The effects of size changes on haptic object recognition

We are capable of visually recognising objects despite variations in size (e.g. Jolicoeur, 1987; Uttl, Graf, & Siegenthaler, 2007). There are two distinct aspects to this capability. The first is our ability to perceive physical rather than retinal size. A nearby object projects a larger retinal image than an identically sized object that is farther away, and yet we do not typically perceive the more distant object to be smaller. Thus, although retinal image size is a product of both the physical size of an object and the distance of the object from the observer, we normally perceive an object's size to be close to its physical size. This ability is called size constancy. The second aspect is our ability to generalize recognition of objects across physical size changes; thus, we can say that a small cup and a large cup are both cups. It is this latter ability to generalize over physical rather than retinal size changes that we will address in this Chapter. Specifically, we will consider how the haptic and visual modalities compare in their ability to generalize across physical size changes.

5.1.1 Visual size-change effects

A considerable body of research has examined how size changes affect visual object recognition. Jolicoeur (1987) reported a size-change cost in old/new recognition with line drawings of familiar objects. Participants were shown either large or small pictures of objects at study; at subsequent test, half of the shapes were shown at the same size as at study, and half were shown at the other size. Recognition was slower and less accurate when objects changed size from study to test. Biederman and Cooper (1992; see also Fiser & Biederman, 1995) tested priming of naming and same/different matching of line drawings of familiar objects. In three experiments, participants saw these drawings twice; half were shown at the same size both times and half were shown at different sizes. Size changes did not affect priming of naming but impaired same/different matching. Cooper, Schacter, Ballesteros, and Moore (1992) showed participants line drawings of structurally possible or impossible unfamiliar objects. Size changes did not affect priming of structural possibility judgments but impaired old/new recognition. Uttl, Graf, and Siegenthaler (2007) showed participants colour photographs of common objects against a blank background. These photographs were scaled to give three different sizes of each object. Participants rated the familiarity of the objects in the photographs then completed either a naming or an old/new recognition task immediately after the study phase, and again one week later. Naming was not affected by size-changes from study to test. Recognition was close to ceiling in the immediate test. In the delayed test, size-changes impaired old/new recognition, but only when large versions of objects were seen at test.

Together these studies suggest that size changes incur a cost for old-new recognition and matching (though not for priming) tasks. However, this cost could be due to either physical or retinal size changes since all of these studies presented 2D images of isolated 3D objects on a computer monitor. With no context in which to place the objects other than the monitor itself, the visual system could have interpreted size changes as either due to alterations in the 3D physical size of the object or due to variation in the distance of the object from the observer. The latter would alter retinal but not physical size. Milliken and Jolicoeur (1992) investigated the latter possibility by manipulating participants' distance from the stimulus as well as stimulus size. Participants saw 2D, novel, line drawings presented on a monitor. They studied the small shapes from a distance of 66cm, and large shapes from

132cm. At test, they then saw some objects from the same distance and some from the different distance and performed an old-new recognition task. When objects were seen at the same distance, same-sized objects were the same retinal size at study and test, whilst changed-size objects were different retinal sizes at study and test. Conversely, when objects were seen at the different distance, same-sized objects were different retinal sizes at study and test, whereas changed-size objects were the same retinal size at study and test. If size-change effects in recognition were due to retinal size, performance should have been better for same-sized objects in the same-distance condition, but better for changed-size objects in the different-distance condition. Instead, recognition was better for same-sized objects in both conditions, indicating that physical rather than retinal size was driving size-change costs.

Bennett and Warren (2002) also attempted to dissociate retinal size from physical size. They presented randomly constructed, silhouetted, statue-like stimuli placed in a checkerboard hallway on a computer screen. On each trial, two identical or two different shaped stimuli were presented simultaneously. The relative retinal and physical sizes of these object pairs was varied. Participants judged whether the two objects were the same or different shapes. Response times increased as both retinal and physical size differences between the two objects increased. However, both stimuli were visible simultaneously. Stored representations may be less sensitive to retinal size so effects of physical size might dominate those of retinal size in a task where memory is required.

Finally, people's estimates of the size of projections of objects on mirrors and windows are strongly biased towards the physical rather than projected size of the objects (Lawson & Bertamini, 2006; Lawson, Bertamini, & Liu, 2007). For example, people typically estimate the projected size of their face on the surface of a mirror as being close to the actual, physical size of their face, irrespective of viewing distance. However, this projection is always half the width and half the height of their actual face.

5.1.2 Size effects in haptics and vision

There are good reasons to expect that size might influence haptic object recognition differently to visual object recognition. Distance cues and retinal size both contribute to the visually perceived size of an object (Haber & Levin, 2001). Visual estimation of physical size occurs automatically (Goldfarb & Tzelgov, 2005) and begins in early visual cortex (Murray, Boyaci, & Kersten, 2006). However, while vision combines both direct, object-specific cues and indirect, environmental cues, haptics normally perceives size only through direct contact. An inverse relationship between distance and perceived size has been observed when haptic perception is extended by means of a wooden rod (Barac-Cikoja & Turvey, 1995). However, in most circumstances there is no distance between the hands and the object being perceived haptically. Typically, haptically perceived size depends on several factors including the spread of the fingers on initial contact with an object and the compliance of the object's surface (Berryman, Yau, & Hsiao, 2006). Prolonged visual experience can modulate the perceived distance between two points of contact on the skin (Taylor-Clarke, Jacobsen, & Haggard, 2004) but such modulation is probably rare in everyday life. An object's size and shape place constraints on how it is grasped, so an accurate representation of size is important for object manipulation. The action of grasping itself is similar to enclosure, an exploratory procedure particularly associated with the haptic perception of size (Lederman & Klatzky, 1987). However, Westwood and Goodale (2003) found that although a size-contrast illusion decreased the accuracy of haptic size estimation, grip-aperture was unaffected, suggesting that there may be a dissociation between haptic size perception and grasping.

Information about physical size may be more important for haptic compared to visual object recognition since fewer alternative sources of information may be available haptically than visually. Furthermore, compared to alternative object properties, size information may be relatively more reliable for haptics than vision. If, relative to other cues, size information is easier to extract, more reliable or is weighted more highly by haptics than by vision, then size changes may perturb haptic more than visual processing.

There is evidence that haptics and vision may differ in their relative weighting of different sources of information. For example, Cooke et al. (2007) investigated the relative importance of object features such as shape and texture across visual and haptic modalities in a similarity rating study. They found that although vision and haptics use broadly similar perceptual maps when comparing stimuli, shape was much more important than texture for vision whereas shape and texture were similarly important for haptics. In a free-sorting task, Lederman, Summers, and Klatzky (1996) found that shape was the most salient dimension for both vision and touch, and that shape was more salient for vision than for touch. Size was as rapidly available as shape to haptics, but it was not a salient dimension either for vision or touch. Similarly, Klatzky et al. (1987) found evidence that size information may be given little weight by either vision or haptics. When participants were directed to sort stimuli along one of several dimensions, both visual and haptic size sorting was poor, and when freely sorting these stimuli by similarity, size was the least frequently used dimension. Similar to Cooke et al. (2007), material qualities were more salient to touch than to vision. However, Reed, Lederman, and Klatzky (1990) found that size was weighted strongly by participants who had to learn to haptically classify a set of 2D planar stimuli. The stimuli varied in size, shape, texture, and hardness. When classes defined by two dimensions (e.g., size and shape) were learnt, removing the size cue disrupted performance more than removing the other three cues. Furthermore, even when exploratory procedures were restricted to contour following, size information was still available although the procedure normally used to detect size, enclosure, was not available.

There is thus some evidence for the importance of size to haptic classification, but only one study, reported by Srinivas et al. (1997), has specifically examined the interaction between input modality and the effect of size changes on object recognition. Srinivas et al. (1997) compared memory for visually and haptically perceived 2D novel patterns. They presented novel, three-line patterns drawn on paper in the visual condition and as raised lines in the haptic condition. At study, participants described the patterns. At test, each stimulus was presented again at either the same or a different size and orientation. Participants either drew each stimulus or performed an old/new recognition task. Orientation changes from study to test worsened both visual and haptic drawings whereas size changes worsened only the haptic drawings. Both orientation and size changes disrupted recognition to a similar extent for both visual and haptic modalities.

The results of Srinivas et al. (1997) provide evidence for broadly similar representational strategies across the two modalities. However, the disruptive effect of size changes on haptic but not visual drawings suggests that size may be a more important factor for haptic as opposed to visual object recognition (see also Reed et al., 1990). Both Reed et al. (1990) and Srinivas et al. (1997) used simple, 2D stimuli which lacked many of the features to which haptic perception is best attuned, and limited the use of typical haptic exploratory procedures (Klatzky et al., 1987; Lederman & Klatzky, 1987, 1990). Lawson (2009) has shown that people are able to haptically recognise small-scale models of familiar objects quite efficiently. The models included stimuli for which people would have had little or no direct haptic experience such as canoes, submarines, and various animals. In the present studies we tested the recognition of more ecologically valid everyday 3D objects using priming of naming (Experiment 8) and old/new recognition (Experiment 9).

5.2 Experiment 8

Experiment 8 compared the effects of size changes across the visual and haptic modalities using a naming recognition task. We formulated two alternative hypotheses. First, as outlined above, and consistent with the results of the drawing task reported by Srinivas et al. (1997), size may be of greater diagnostic value to haptic than to visual object recognition. If so, then size changes may disrupt haptic performance more than visual performance. Second, vision and haptics may both use the same rescaling processes to match different sized exemplars of a given category to a more abstract, general representation for recognition. Thus, both modalities may display similar costs to achieve generalization over size changes. Previous evidence in the visual domain suggests that visual priming should be unaffected by changes in size from study to test.

These two hypotheses about the relative importance of size information for haptic and for visual object recognition need to be tested by comparing haptic to visual performance on the same task. Objects must normally be within reach to be explored haptically, and they must therefore be placed within a clearly defined spatial context. In contrast, visual experiments have usually presented 2D images of 3D objects shown in isolation on a computer monitor with no background and without strong cues to their actual physical size or 3D location (e.g. Biederman & Cooper, 1992; Cooper et al., 1992; Fiser & Biederman, 1995; Jolicoeur, 1987; Uttl et al., 2007) or visual studies have presented novel, 2D objects, again with no meaningful background (Milliken & Jolicoeur, 1992; Srinivas et al., 1997). Without information about the spatial location of an object, it is impossible to distinguish between physically larger and physically closer objects. Although Bennett and Warren (2002) attempted to dissociate these processes by picturing objects within a spatial context, they did not test the size-specificity of longer-term memory.

In Experiment 8, we attempted to maintain similar conditions for both modalities. Two separate groups of participants took part in the visual and haptic conditions. In the first of the two experimental blocks, participants named one of three exemplars of 36 categories of familiar object: a standard exemplar, a different size but similar shape exemplar, or a different shape but similar size exemplar. In the second block, participants named the standard exemplars of the same 36 familiar objects intermingled with 25 new familiar objects.

We presented different shape exemplars to test the possibility that minor shape changes may cause any differences we observed in performance on size-change trials. Real objects were used in these experiments and so there were usually minor shape changes between the different size exemplars (e.g. between a large and small cup) in addition to the size change. The different shape exemplars were chosen to be similar in size to the standard objects but to have different shapes (see Figure 5.1). If any effects of size changes were caused by minor shape changes then the shape-change trials should elicit much larger costs to performance. However, if size changes per se influence object recognition then size-change trials should produce a cost to priming at least as large as that for shape-change trials.

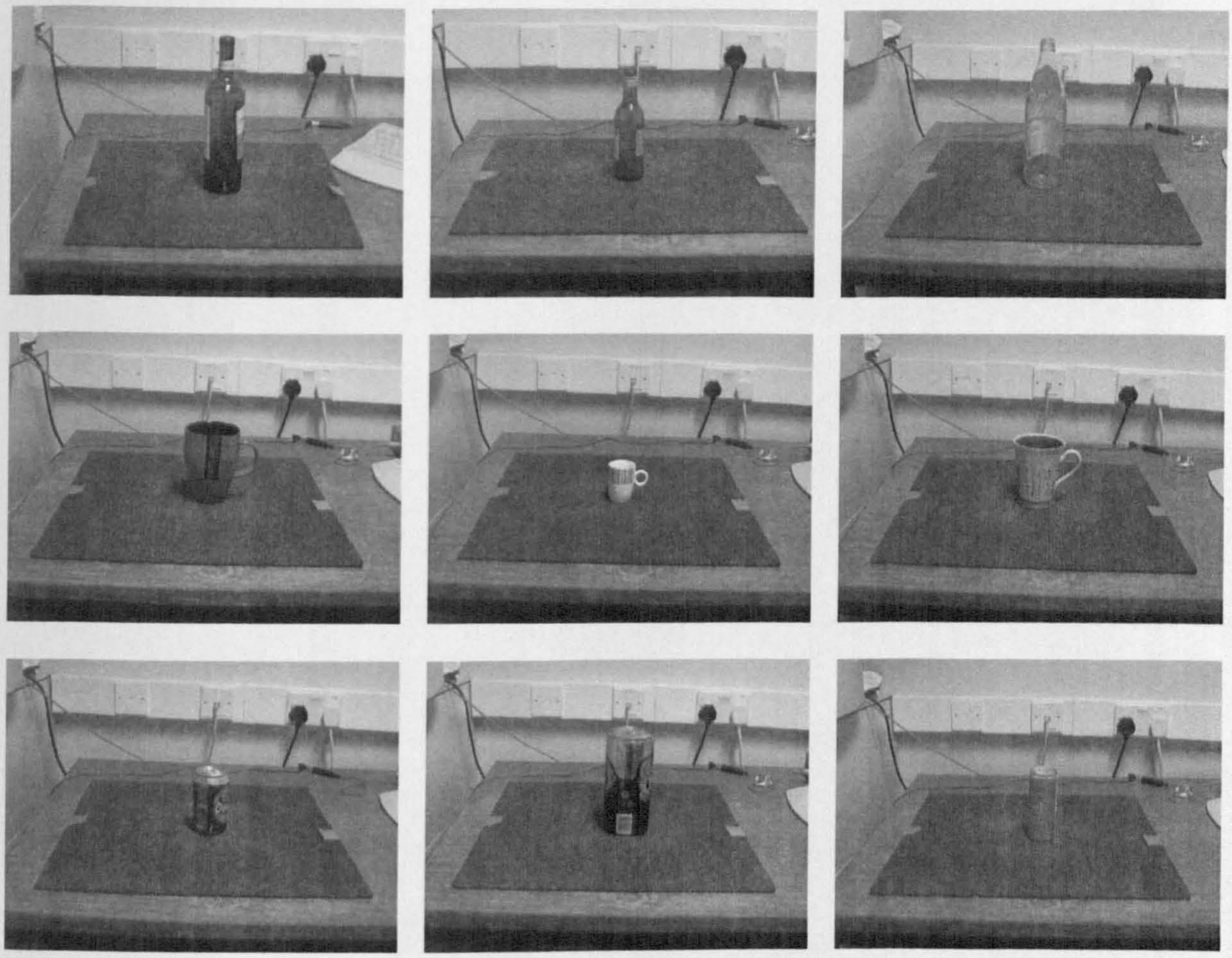

Figure 5.1. Three of the old objects (bottle, cup, and can) which were presented as 3D stimuli in the context depicted in these photographs in the haptic condition and which were presented as the photographs shown here in the visual condition. On each row, photographs from left to right show the standard, different size, and different shape exemplars. The direction and magnitude of size change varied across items; here, the different size bottle and cup are smaller than the standard exemplar, while the different size can is larger.

In the haptic condition, real, 3D objects were presented to blindfolded participants. In the visual condition, greyscale 2D photographs of the same objects were presented on a computer screen. These photographs depicted the objects in the same location as they were presented in the haptic condition and from a height and angle approximately on the line of sight of the observers in the haptic condition, see Figure 5.1. Thus, unlike previous visual size change experiments, visual objects were presented within a well-specified and constant 3D spatial context that contained many cues to their physical size. In particular, it was clear that in the size-change condition different sized objects were presented rather than the same objects at a different distance. The visual version of our task thus extended Milliken and Jolicoeur's (1992) test for effects of size changes where distance could not be a confounding factor.

5.2.1 Method

Participants

Sixty participants were recruited from the student population of the University of Liverpool. Ages ranged from 18 to 37. Thirty participants participated in the visual condition, 30 in the haptic condition.

Stimuli

Sixty-one familiar categories of objects were presented either haptically or visually in the haptic and visual conditions respectively. Three exemplars of 36 of these object categories were used as the old objects, see Figure 5.1. The remaining 25 objects were used as new objects, and were standard size and standard shape exemplars of their category, see Appendix IV. See the Supplementary CD for a full set of photographs of these objects. Five more objects were used as practice items. One exemplar had a standard size and shape (standard); another exemplar had a different size but similar shape to the standard (different size); the third exemplar had a similar size but different shape to the standard (different shape). The standard exemplar was a typical size and shape for exemplars of that category.

We verified the selection of these exemplars using a set of visual rating studies. Twenty undergraduate students at the University of Liverpool (aged 18-20 years) who did not take part in the other experiments rated photographs of each of the three exemplars of the 36 old object categories on a scale of 1 (low) to 7 (high) for typicality and for similarity of the different-size and different-shape exemplars to the standard exemplars. All participants rated the typicality of all three exemplars of each object. Standard exemplars were rated as more typical (5.3) than different-size (4.9) and different-shape (4.8) exemplars. Ten of these participants were then shown pairs of photographs and they rated the exemplar pairs for similarity. For each object category, they were shown the standard exemplar twice, paired once with the different size exemplar and once with the different shape exemplar. Different-size (4.7) exemplars were rated as more similar to the standard exemplars than were the different-shape (4.2) exemplars. The other 10 participants were shown trios of photographs of each object category and they chose which of the different size and different shape exemplars was most similar to the standard exemplar. Participants chose different-size exemplars as more similar on 66% of trials. These ratings studies thus supported the classification of the object exemplars, see also Appendix III.

As a further verification of the selection of the exemplars, we averaged the height, width, and length of each object to obtain an estimate of its size. For each category of old object, we then divided the size estimate for the different size exemplar and for the different shape exemplar by the size estimate of the standard exemplar and multiplied this proportion by 100. This provided an estimate of the size of these exemplars as a percentage of the size of the standard exemplar. A different size exemplar that was smaller than its standard exemplar (such as the bottle) had a relative size estimate that was less than 100%, while a different size exemplar that was larger (such as the can) had a relative size estimate greater than 100%. The size change relative to the standard was simply calculated as the difference from 100%, so if the relative size of a different shape exemplar was 90% of the standard exemplar then the estimated size change relative to the standard was 10%. On this estimate, the size change relative to the standard for the different size exemplars (on average, ±45%) was much greater than that for the different shape exemplars (±13%). Figure 5.2 shows a histogram of the distribution of the estimated size changes for the different size and different shape exemplars. Note that most of the different size exemplars were smaller than the standard exemplars.

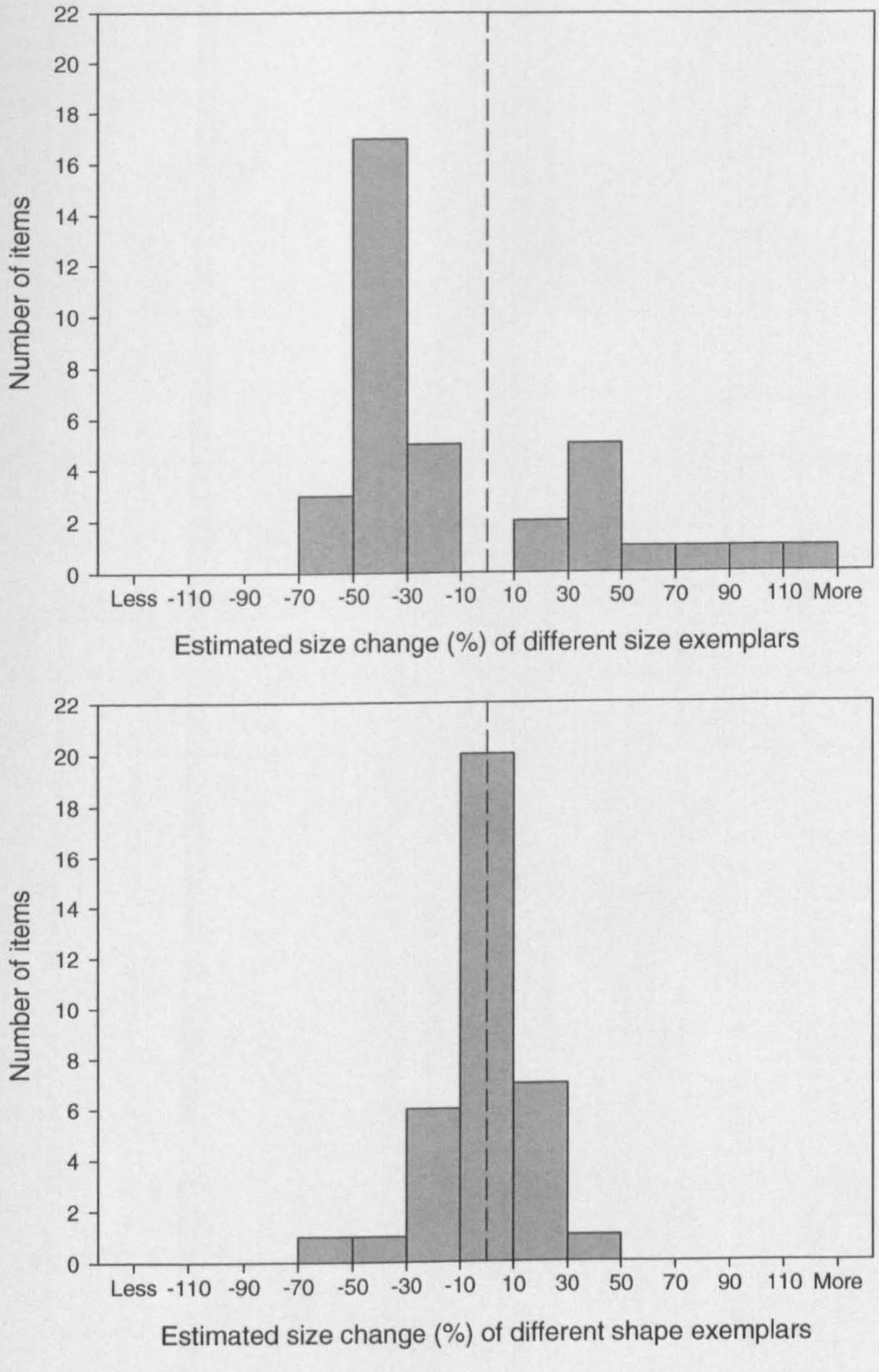

Figure 5.2. Frequency histograms (Bin size = 20) depicting the amount by which the different size exemplars (top panel) and different shape exemplars (bottom panel) differed in size from the standard exemplars. The dashed line represents zero.

In the haptic condition, the actual objects were presented. In the visual condition, greyscale photographs of the objects were presented. These photographs depicted the objects in the same experimental context, location, and position in which they were presented in the haptic condition. Colour was removed since this could have provided a visual cue to recognition that was not available for haptics. All photographs were taken from a fixed distance of approximately 1m and a fixed angle approximately along the line of sight of the observers in the haptic condition. Participants were seated approximately 60cm from the 17" monitor on which the photographs were presented. The full photographs all subtended a visual angle of 18° x 23°. The average visual angles of the objects shown in the photographs were quite similar across the three types of exemplar, at around 3° x 3°. The average difference in visual angle between the standard exemplars and different size exemplars was ±1.5° x ±1.5°, whereas between the standard exemplars and the different shape exemplars it was ±0.4° x ±0.6°. Thus the visual angle of different size exemplars differed more from that of standard exemplars than the visual angle of different shape exemplars.

Design and Procedure

The visual and haptic participants were allocated to three subgroups, and the old objects were divided into three sets of 12 items. In the first naming block, each subgroup was presented with the standard exemplars from one set, the different size exemplars from another set, and the different shape exemplars from the final set. The sets allocated to each subgroup at study were counterbalanced using a Latin Square design. Standard exemplars of all of the old and the new objects were presented in the second naming block.

All participants first read a list of the names of the experimental objects. In the haptic condition, participants were then shown the 50 cm^2 carpet tile on which the objects would be placed and the starting positions in which they should place their hands. These positions were indicated by pieces of masking tape at the centre of the left and right edges of the carpet tile (see Figure 5.1). The tape allowed participants to locate the starting hand positions consistently without vision. Carpet tile was used to muffle sounds made by placing the objects. Participants then put on a pair of safety goggles covered in masking tape and confirmed that they were unable to see the area in which the objects would be placed.

All participants were given five practice trials in which they named objects. Participants then completed the study block of 36 naming trials and then the test block of 61 naming trials. Participants were given a brief break between the two experimental blocks. They were not informed that objects would be repeated. During the break in the haptic condition, the objects were hidden and participants were allowed to remove the goggles.

In the haptic condition, the experimental software package PsyScope 1.2.5 (Cohen et al., 1993) generated the order of presentation of objects and was used to record responses. In the first block, objects were presented in a random order. In the second block, objects were presented in a pseudo-randomly determined order. The order of trials in the first block was randomized for each participant, but the order of trials in the second block was the same for all participants. On each trial, the experimenter placed an object in the centre of the carpet tile in a fixed orientation in depth, then started each trial once the participant had positioned their hands on the tape markers. A single low-pitched warning beep was played, followed by a high-pitched double-beep 1s later to indicate that participants could start to move their hands to touch the object. Single, low-pitched beeps then occurred every second for the next 3s, followed by a high-pitched double-beep 4s after the starting double-beep. This indicated that participants should stop touching the object and return their hands to the starting position. Participants were informed that they should use both hands to explore the object freely, and they were allowed to lift it.

In both blocks, participants were given up to four seconds to haptically explore each object and trials ended only when the participant had made a response. Trials on which they responded after the final double-beep were not classed as errors. In the first block, participants were instructed to name the objects both quickly and accurately, ceasing exploration as soon as they had named the object or the second double-beep sounded. In the second block, participants were instructed to name the objects both quickly and accurately. Response times were recorded using a microphone headset attached to a Macintosh computer as a voice key. The experimenter recorded incorrect responses, trials on which the microphone was activated before the participant responded (voice key errors), and trials on which the participants started to move before the starting beep (movement errors). No feedback on accuracy was provided.

In the visual condition, the experimental software package E-Prime 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA) was used to generate the order of presentation and record response times. As in the haptic condition, the objects were presented in a random order in the first block, and presented in a fixed, pseudo-randomly determined order in the second block. On each trial, participants heard a single beep, then a double beep. The photographs appeared in the centre of the screen when the double beep sounded. The photographs disappeared when the participants responded. Unlike the haptic trials, there was no fixed presentation time since visual naming is typically much faster than haptic naming. Response times were recorded using a microphone connected to a Windows PC via an E-Prime response box. The experimenter recorded incorrect responses and voice key errors. No feedback on accuracy was provided.

5.2.2 Results

The results from the haptic and visual conditions were analyzed separately. The results from both conditions were analyzed using mixed analyses of variance (ANOVA) conducted on the mean of median correct naming response times (RTs) and mean percentage errors in by-participants and by-items analyses. Block (Block 1 or Block 2) and study exemplar (standard, different size, or different shape) were used as within-participants/items factors. Subgroup (which set of old items was assigned to each study exemplar condition) was used as a between-participants factor and object set was used as a between-items factor. Effects involving these latter two counterbalancing factors were not of theoretical interest and so they are not reported.

Trials were excluded from RT analyses if voice key errors (haptic: 4%; visual: 5%), movement errors (haptic only: 2%), or naming errors in block 1 (see below) occurred. Trials for which voice key, movement, or naming errors occurred in block were also excluded from the RT analyses in block 2, and vice versa. Haptic RTs less than 750ms or exceeding 10,000ms were discarded as errors (less than 1% of trials). Visual RTs less than 375ms or exceeding 5,000ms were discarded as errors (less than 1% of trials). Both cut-offs applied to both blocks. Note that there was some overlap between the error types classified above: For example, both naming and voice key errors occurred on some trials. All results are reported as significant at $p < .05$. Bonferroni correction for multiple comparisons was used on all post-hoc pairwise comparisons.

Visual naming

Naming was 146ms faster [$F_p(1,29) = 92.129, p < .001$; $F_i(1,33) = 31.509, p < .001$] and 4% more accurate [$F_p(1,29) = 31.820, p < .001$; $Fi(1,33) = 11.131, p = .002$] in Block 2

(859ms; 6%) than in Block 1 (1005ms; 10%). Thus, there was a reliable priming effect in visual naming.

There was an effect of study exemplar for RTs [$F_p(2,58) = 4.543$, $p = .02$; $F_i(2,66) = .301$, $p = .7$] but not for errors [$F_p(2,58) = .476$, $p = .6$; $F_i(2,66) = .497$, $p = .6$]. Standard exemplars (901ms; 8%) were named 58ms faster but no more accurately than different size exemplars (959ms; 7%) but neither faster nor more accurately than different shape exemplars (935ms; 8%).

There was a marginal trend towards an interaction between block and study exemplar for RTs [$F_p(2,58) = 3.132$, $p = .05$; $F_i(2,66) = .627$, $p = .5$] but not for errors [$F_p(2,54) = .376$, $p = .7$; $F_i(2,66) = .104$, $p = .9$], suggesting that any effects of changes of exemplar on priming were weak, see Figures 5.3 and 5.4.

Haptic naming

Naming was 561ms faster [$F_p(1,29) = 30.725$, $p < .001$; $Fi(1,33 = 25.341$, $p < .001$] and 2% more accurate [$F_p(1,29) = 8.817$, $p = .006$; $Fi(1,33) = 6.693$, $p = .01$] in Block 2 (3097ms; 6%) than in Block 1 (3658ms; 4%). There was therefore a reliable priming effect for haptic naming.

There was an effect of study exemplar for RTs [$F_p(2,58) = 14.821$, $p < .001$; $F_i(2,66) = 6.329$, $p = .003$] and for errors [$F_p(2,58) = 8.300$, $p = .001$; $F_i(2,66) = 4.424$, $p = .02$]. Standard exemplars (3065ms; 6%) were named 504ms faster but no more accurately than different size exemplars (3569ms; 7%) and 434ms faster but no more accurately than different shape exemplars (3499ms; 3%). Different shape exemplars were also named significantly more accurately – by 4% - than different size exemplars.

There was no interaction between block and exemplar for RTs [F_p (2,58) = .029, $p >$ .9; F_i(2,66) = 1.601, $p = .2$] but there was for errors [F_p(2,58) = 8.044, $p < .001$; F_i(2,66) = 5.370, $p = .007$].

To decompose the interaction for errors, we conducted separate ANOVAs for each block. In Block 1 there was a significant effect of study exemplar on errors [F_p(2,54) = 16.975, $p < .001$], see Figure 5.3. Standard exemplars (6% errors) more accurately than different size exemplars (10%), but 4% less accurately than different shape exemplars (2%). Different shape exemplars were also recognised 8% more accurately than different size exemplars.

In Block 2 there was no effect of study exemplar on errors [F_p(2,54) = .388, $p = .7$], see Figure 5.4. Objects that were the same size and shape in both blocks (2793ms; 5%) were recognised faster – by 495ms and 417ms – but no more accurately than objects that had changed size (3288ms; 5%) or changed shape (3211ms; 4%) from study to test. New objects were not included in the analysis (3942ms; 6%). Errors were only affected by study exemplar in Block 1.

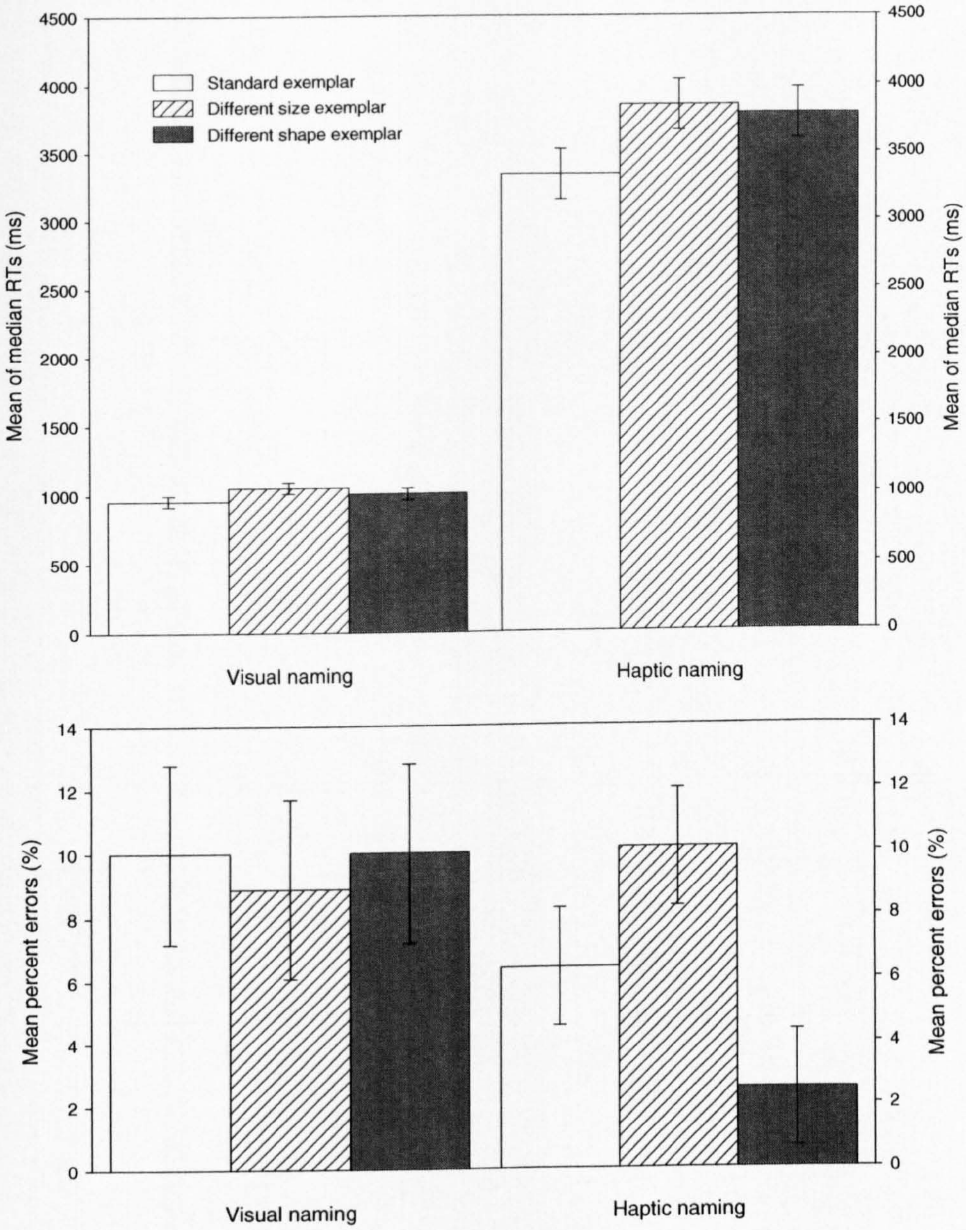

Figure 5.3. Mean of median naming RTs (ms; upper graph) and mean percent naming errors (%; lower graph) for the visual and haptic conditions in Block 1. Bar shading indicates the exemplar presented in Block 1; all objects presented in Block 2 were standard exemplars. Error bars are 95% within-participant confidence intervals (Loftus & Masson, 1994).

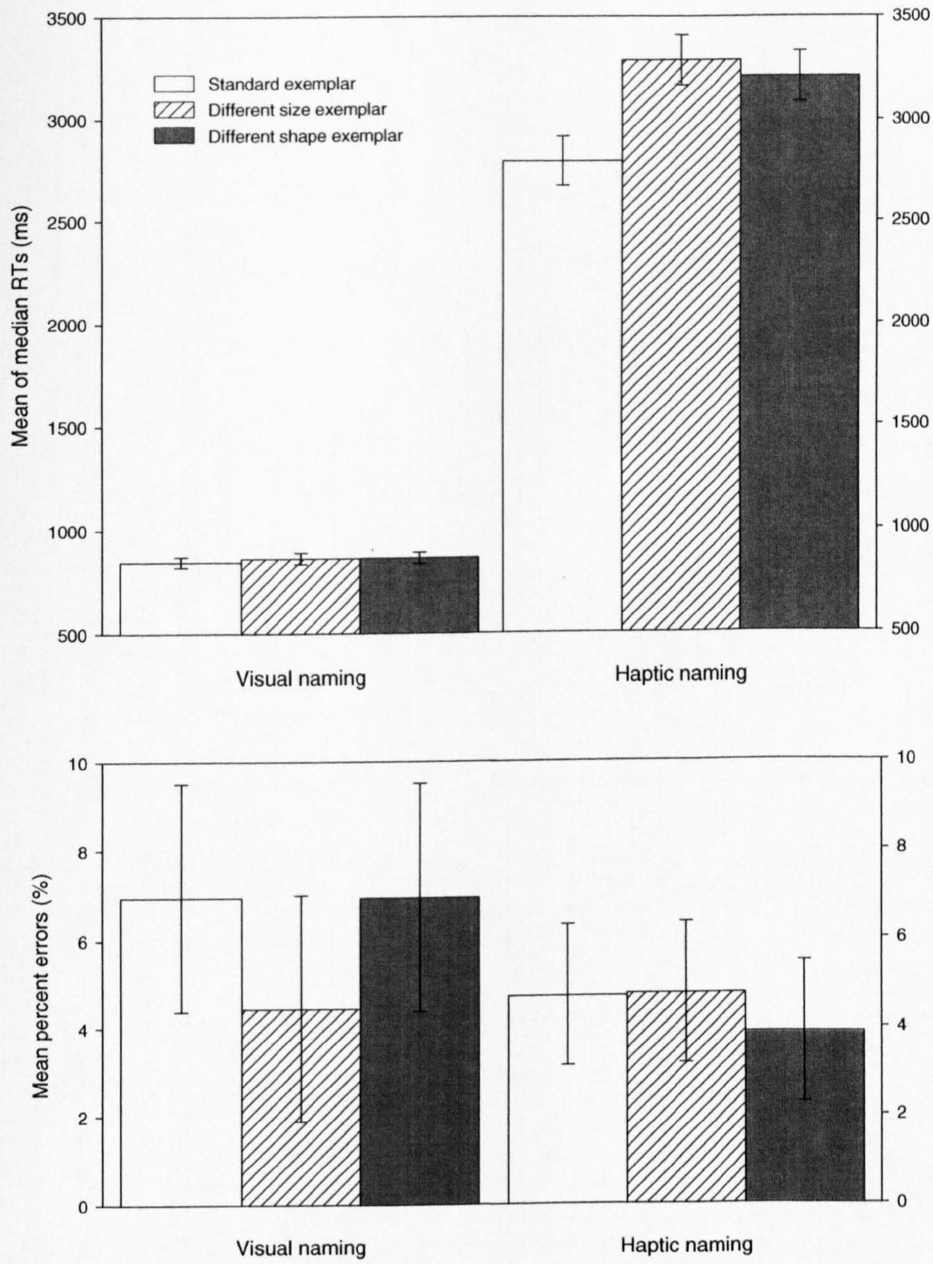

Figure 5.4. Mean of median naming response times (RTs; upper graph) and percent errors (%; lower graph) for the visual and haptic conditions in Block 2. Bar shading indicates the exemplar presented in Block 1; all object presented in Block 2 were standard exemplars. Error bars depict 95% within-participant confidence intervals (Loftus & Masson, 1994).

5.2.3 Discussion

In both visual and haptic naming, different size and different shape exemplars were named slower than standard exemplars. These differences may be due to differences in the typicality of the exemplars, since standard exemplars were more typical than different size or different shape exemplars. There was also a clear priming effect for both visual and haptic naming. Naming was both faster and more accurate in the second block for all previously named object categories in both the visual and haptic modalities, irrespective of whether the objects had changed size or shape between blocks. However, there was little to no effect of either size or shape changes on priming of for either visual or haptic naming. The interaction for errors in the haptic naming condition was not in the expected direction: differences in errors were apparent only in the first block, and thus priming was unaffected by such changes.

Although this result is similar to Biederman and Cooper's (1992) finding that priming of naming was unaffected by size changes, and is also comparable to the lack of effect of changes of orientation on name priming in Experiment 1 (Chapter 2), there are some notes of caution. As discussed in Chapter 2, implicit measures such as priming of naming are often statistically weak and unreliable (Buchner & Brandt, 2003; Buchner & Wippich, 2000). Thus, as in Chapter 2, a further experiment using a more reliable, explicit measure of recognition memory was conducted.

5.3 Experiment 9

Whereas Experiment 8 tested priming of naming, in Experiment 9 participants performed an old/new recognition task using the same stimuli and first block naming task in Experiment 8. Old/new recognition was expected to provide a clearer picture of the relative sensitivities of vision and haptics to size changes.

5.3.1 Method

Participants

Sixty right-handed students from the University of Liverpool participated in return for course credit. Handedness was self-reported, and their ages ranged from 18 to 36 years. Thirty participants took part in the haptic condition, and 30 in the visual condition.

Stimuli

The same stimuli were used as in Experiment 8.

Design and procedure

The same procedure was used as in Experiment 8, with the exception that participants performed an old/new recognition task at test rather than naming the objects. Participants were told to disregard any physical changes in the objects and to base their decision on the objects' names.

5.3.1 Results

The results were analyzed using mixed analyses of variance (ANOVA) conducted on median correct response times (RTs) and percentage errors in by-participants (F_p) and by-items (F_i) analyses for naming responses in block 1 and old/new recognition memory in block 2. Study exemplar (standard, different size, or different shape) was used as a within-participants/items factor. Subgroup (which set of old items was assigned to each study exemplar condition) was used as a between-participants factor and object set was used as a between-items factor. Effects involving these latter two counterbalancing factors were not of theoretical interest and so they are not reported.

It would have been interesting to compare the two conditions directly using modality as a between-participants factor. However, the variances of the visual RTs were much lower than those of the haptic RTs. This led to a violation of the ANOVA's assumption of homogeneity of variance and a consequent loss of statistical power. Normalizing the RT distributions using procedures such as logarithmic or inverse transformations did not solve this problem. As such, we analyzed the results from the haptic and visual conditions separately. This assumption was not violated for errors, but since the interaction between exemplar and modality was not significant for errors, then for ease of interpretation we report both RT and error analyses separately for each modality.

Trials were excluded from the RT analyses if voice key errors (haptic: block 1, 6%; block 2, 2%; visual: block 1, 8%; block 2, 4%), movement errors (haptic only: 1% in both blocks), or naming errors in block 1 (haptic: 9%; visual: 5%) occurred. Trials for which voice key, movement, or naming errors occurred in block 1 were also excluded from the RT analyses in block 2, and vice versa. Trials on which naming errors occurred in block 1 were also excluded from the error analyses in block 2. Haptic RTs less than 750ms or exceeding 10,000ms were discarded as errors (less than 1% of trials). Visual RTs less than 375ms or exceeding 5,000ms were discarded as errors (less than 1% of trials). Both cut-offs applied to both blocks. Note that there was overlap between the error types classified above: for example, both voice key and naming errors occurred on some trials. Altogether, 12% of trials were excluded under these criteria in both the haptic and visual analyses.

Three participants in the haptic condition were replaced as they committed voice key errors on over 18% of trials. No participants were replaced in the visual condition. All results are reported as significant at $p < .05$. Bonferroni correction for multiple comparisons was used on all post-hoc pairwise comparisons. Tukey's HSD tests were conducted on significant interactions. There was no indication of a speed/accuracy trade-off in any condition.

Block 1

Haptic naming. There was no effect of study exemplar on either naming RTs [$F_p(2,54) = 2.291, p = .1$; $F_i(2,66) = 2.270, p = .1$] or errors [$F_p(2,54) = 2.024, p = .1$; $F_i(2,66) = .798, p = .5$]. Standard (2952ms, 8% errors), different size (3081ms, 12%), and different shape (3084ms, 9%) exemplars were all named similarly quickly and accurately, though there was a trend for different size and different shape objects to be named slower – by 129ms and 132ms respectively - than the standard objects.

Visual naming. There was a significant effect of study exemplar on naming RTs for participants only [$F_p(2,54) = 5.438, p = .007$; $F_i(2,66) = 2.194, p = .1$] but not on errors [$F_p(2,54) = .258, p > .8$; $F_i(2,66) = .333, p > .7$]. Different size exemplars (1039ms; 5%) and different shape exemplars (1034ms, 5%) exemplars were named slower - by 76ms and 71ms - than the standard exemplars (963ms; 6%), though only the difference between different size and standard exemplars was significant in post-hoc comparisons. The pattern of performance was similar to that observed in the haptic condition.

Block 2

Haptic old/new recognition. There was a significant effect of study exemplar for both RTs [$F_p(2,54) = 16.411, p < .001$; $F_i(2,66) = 16.123, p < .001$] and errors [$F_p(2,54) = 5.729, p = .006$; $F_i(2,66) = 6.092, p = .004$], see Figure 5.5. Post-hoc comparisons revealed that objects which had been studied at a different size (2941ms; 7%) or a different shape (2869ms; 7%) were recognised slower and less accurately – by 295ms and 5% and by 223ms and 5% respectively – than objects which had the same size and same shape at study and test (2646ms; 2%). There was no difference in performance between exemplars studied at different sizes and different shapes. As only standard exemplars were presented at test, all differences were due to differences in the study exemplar. New objects (3184ms, 6%) were not included in the main analysis.

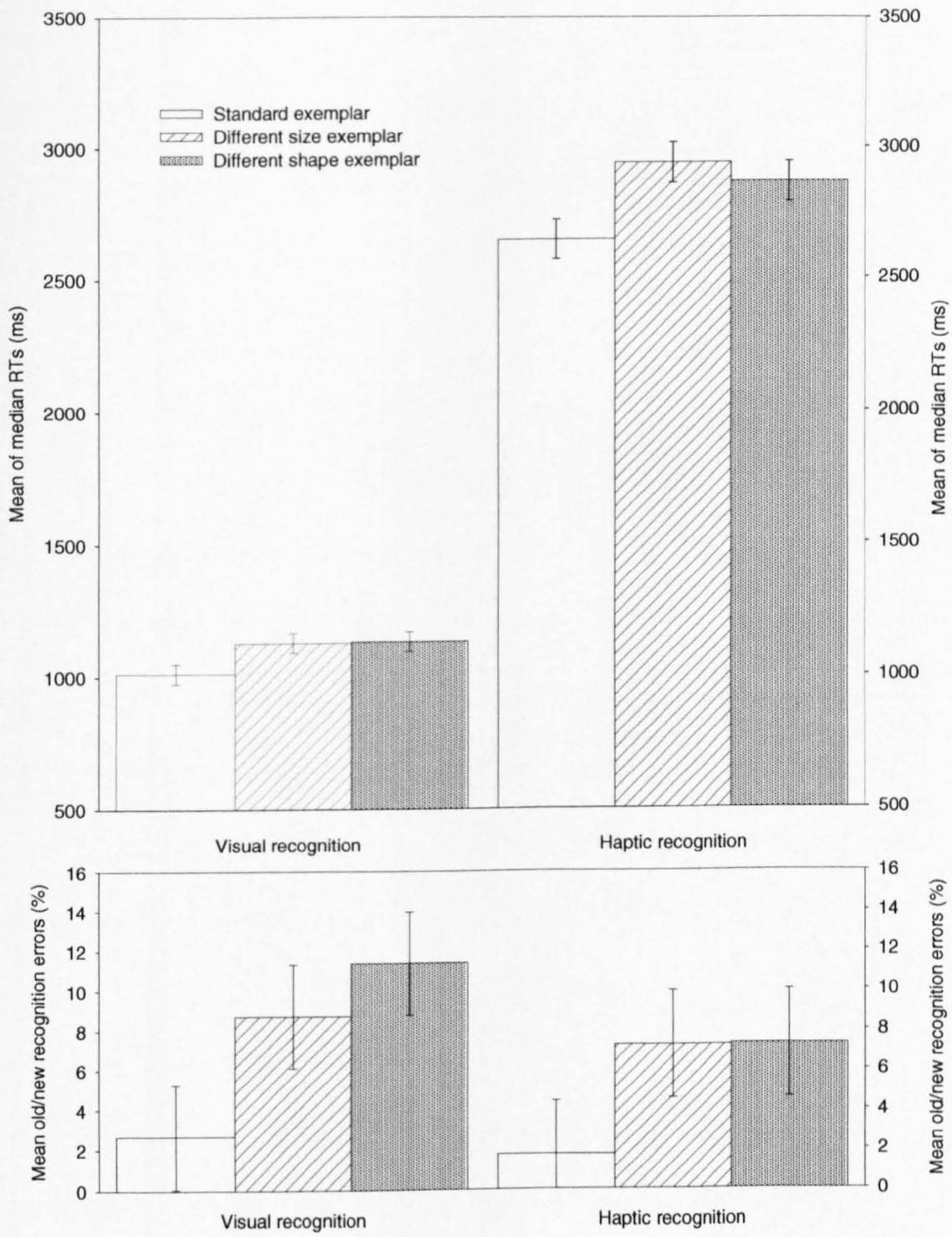

Figure 5.5. Mean of median old/new recognition task response times (upper graph) and percentage errors (lower graph) for the haptic and visual conditions. Bar shading indicates the exemplar presented in Block 1; all objects presented in Block 2 were standard exemplars. Error bars depict 95% within-participants confidence intervals (Loftus & Masson, 1994).

Visual old/new recognition. There was a significant effect of study exemplar for both RTs [$F_p(2,54) = 13.019, p < .001$; $F_i(2,66) = 13.646, p < .001$] and errors [$F_p(2,54) = 10.091, p < .001$; $F_i(2,66) = 6.781, p = .002$], see Figure 5.5. Post-hoc comparisons revealed that objects which had been studied at a different size (1128ms, 9%) or as a different shape (1131ms, 11%) were recognised slower and less accurately – by 116ms and 6% and by 119ms and 8% respectively – than objects which had the same size and same shape at study and test (1012ms, 3% errors). There was no difference in performance between exemplars studied at different sizes and different shapes. As only standard exemplars were presented at test, all differences were due to differences in the study exemplar. New objects (1157ms, 10%) were not included in the main analysis.

Amount and direction of size change, shape similarity, and effects on recognition

We also examined the relationship between the amount of size change, the ratings of shape similarity, and block 2 old/new recognition performance. This analysis was not performed in Experiment 8 since there was no significant effect of size or changes on priming of naming. We correlated the estimated size change, ratings of similarity, and old/new recognition RTs and errors for each category of object. For the latter two measures (RTs and errors), we subtracted performance on standard exemplar trials from performance on the different size and different shape trials to yield a measure of the amount of disruption caused by the change in size or shape respectively. For these analyses, if the estimated size change was negative (so if the different size or shape exemplar was smaller than the standard exemplar), the sign of the size estimate was reversed.

In the haptic condition, there was a significant correlation between estimated size change and RTs in the different shape condition ($r = .36, p = .03$) and a consistent trend in the different size condition ($r = .28, p < .1$). There were also significant correlations between estimated size change and errors in the different shape ($r = .35, p = .04$) and different size ($r = .46, p = .006$) conditions. Thus, in the haptic condition, RTs and errors both increased as the estimated size change increased for both different shape and different size exemplars. Shape similarity ratings for the different size and different shape exemplars did not correlate with RTs, errors, or estimated size change. No significant correlations were observed in the visual condition.

5.3.2 Discussion

In both the haptic and visual conditions, recognition was faster and more accurate when the object was the same size and shape in both blocks compared to when it changed either size or shape. Naming speed and accuracy in block 1 was similar for all exemplar types. Only standard exemplars were presented in block 2, and the block 2 analyses only included data from objects that were correctly named in block 1. Thus, the observed differences cannot be due to differences in identification of the exemplars. Our finding of a cost to generalising over size changes for haptic and visual recognition of familiar 3D objects replicates and extends Srinivas et al.'s (1997) finding of a cost of size changes when haptically and visually recognising simple, 2D novel patterns. The results from the visual condition replicate previous findings of impaired old/new visual object recognition following a size change (Biederman & Cooper, 1992; Fiser & Biederman, 1995; Jolicoeur, 1987; Uttl et al., 2007) and extend them to images of real, 3D objects placed within a rich environmental context. We will consider this result further in the general discussion.

Both the pattern of RTs and errors and the actual error rates were similar across the two modalities. These data did not support the prediction that size changes would disrupt haptic recognition much more than visual recognition. Instead, comparable costs occurred for both modalities despite the striking differences in how they acquire information about size. Furthermore, the costs of haptic size changes were modest in comparison to, for example, the costs to haptic recognition of removing depth information or restricting exploration (Klatzky et al., 1993; Lawson, in preparation; Loomis et al., 1991). Our results therefore suggest that both visual and haptic object recognition cope with size changes quite efficiently.

Shape changes caused similar disruption of old/new recognition memory. This suggests that the perceptual representations formed were both size and shape specific, since different size exemplars were largely the same shape as standard exemplars, while different shape exemplars were of largely the same size as standard exemplars. Given our use of real objects, it was not possible to fully unconfound the causal roles of size and shape changes in the current data. The correlational analyses indicate that size changes may have been a more important modulating factor than shape changes for haptic recognition: significant correlations were only observed for estimated size changes, not for ratings of shape similarity, and there was a significant correlation between estimated size change and the speed and accuracy of recognition following a shape change. Thus some of the cost of recognising objects haptically in the different-shape condition may have been caused by size rather than shape changes.

5.4 General Discussion

In Experiment 8, there was little evidence of an effect of size changes on priming of naming. However, in Experiment 9, we demonstrated that size and shape changes impaired haptic old/new object recognition for real, everyday objects, extending the findings of Srinivas et al. (1997) for novel, 2D line patterns. We also found similar costs in visual old/new object recognition, consistent with previous findings of a cost of size changes in vision (Biederman & Cooper, 1992; Cooper et al., 1992; Fiser & Biederman, 1995; Uttl et al., 2007).

Experiment 9 demonstrated a cost of physical size changes to an object in the visual modality as opposed to retinal size changes resulting from altering the distance between the observer and an object. Our results are consistent with those reported by Milliken and Jolicoeur (1992), who found that size change effects in recognition memory for novel shapes were determined by apparent physical size rather than retinal size. Some previous research has presented photographs of real, familiar objects (e.g. Fiser & Biederman, 1995; Uttl et al., 2007). However, the objects in these studies were depicted in isolation against a blank background, and thus with no indication of the objects' physical size. The visual system could therefore have interpreted size changes in these experiments as being due to either physical size changes or distance changes. The present findings extend these results to real, familiar objects photographed within a standard environmental context. The stimuli unambiguously showed objects at different physical sizes with size cues similar to those found in everyday object recognition. The effects of physical size changes on visual object recognition remain to be tested with 3D objects in a real environmental context. Generalising over visual size changes might be more efficient under these conditions since richer and more consistent depth information would be available. This is an important topic for future research but the present evidence suggests that the visual recognition of real, 3D objects in a spatially well-specified scene will still be disrupted by size changes.

In the introduction, we discussed several reasons why size changes might be expected to disrupt haptic recognition more than visual recognition. No disruption was observed in Experiment 8, but the results from Experiment 9 suggest that when size changes do disrupt performance, they do so similarly in both modalities. This suggests that both modalities may use similar representational strategies to generalize recognition across different sized exemplars. Perceptual object representations in both modalities seem to retain size information, but transformation of different-sized inputs is quite efficient for both haptics and vision.

Lawson (2009) found evidence for good cross-modal, size-invariant transfer of information. She found that scale models of objects could be identified haptically even for objects which were only visually, not haptically familiar (e.g., shark, ship). However, Lawson (2009) also reported evidence that the cause of orientation-sensitivity may differ for visual versus haptic object recognition. As the difficulty of discriminating between different objects on mismatch trials increased, visual recognition became increasingly orientation-sensitive, whereas the orientation-sensitivity of haptic recognition was unaffected. Furthermore, crossmodal visual-to-haptic matching was orientation-sensitive whereas haptic-to-visual matching was orientation-invariant. Thus, while haptic and visual object recognition were superficially similar in that both exhibited modest orientation-sensitivity, the effects of orientation changes differed strikingly dependent on the modality of stimulus presentation and the difficulty of discrimination. This more fine-grained analysis suggests that orientation-sensitive effects may reflect different causes for vision and for haptics. Although in Experiment 9 here we found similar costs of size changes for vision and haptics, further research is needed, manipulating additional factors, before stronger conclusions can be drawn about the relative ability of the visual and haptic systems to ignore size changes.

Overall, for size as for orientation, haptics appears to display surprisingly similar performance to vision when recognising objects given the profound differences in acquiring information across the two modalities. Both modalities show broadly comparable costs in generalizing over size and orientation changes and excellent cross-modal transfer of information. This evidence is compatible with an account of object recognition in which the two modalities, to some extent, share the same processes and representations. In particular, we did not find support for the hypothesis that haptics would reveal a much greater cost for generalising over size changes compared to vision due to the relatively greater accessibility and reliability of size information compared to other cues to haptics.

However, two issues arise from these results. First, our measure of the size changes of the stimuli used in the experiments in this chapter was only an approximation, and the amount and direction of size change varied across items. In the following Chapter, size changes were controlled more systematically using pairs of custom-made objects which were identical other than a 75% size change. These stimuli allowed us to manipulate size independently of shape changes. A second advantage of using these stimuli is that it allowed us to use the apparatus used in Chapter 3, the sequential matching study of the effects of orientation at different ISIs, to present the actual stimuli to both vision and haptics in the same environment. The wide range of shapes and sizes in the stimulus set used in Experiments 8 and 9 in this Chapter rendered such a comparison impractical. The custom-made stimuli used in Chapter 6, in contrast, were perfectly scaled for use in the visuo-haptic presentation apparatus. Furthermore, this allowed crossmodal matching to be tested, providing more direct evidence regarding the sharing of representations between vision and haptics than in the comparisons across unimodal experiments discussed in this Chapter.

CHAPTER 6| Crossmodal effects of size-changes

This chapter is adapted from Craddock, M., & Lawson, R. (2009b). Size-sensitive perceptual representations underlie visual and haptic object recognition. *PLoS ONE, 4*(11), e8009, doi: 10.1371/journal.pone.0008009

6.1 Size-sensitive perceptual representations underlie visual and haptic object recognition

In Chapter 5 (see also Craddock and Lawson, 2009a), we established that there are similar costs of size changes for visual and haptic familiar object recognition. In this Chapter, we will examine whether size-sensitive representations are modality-specific or are shared across the visual and haptic modalities.

One problem with comparing the effects of variations such as orientation on different modalities is that it is not clear how to match changes across modalities. We will argue that, in contrast to orientation, the effects of size changes may be relatively straightforward to equate across vision and haptics. This means that it is of particular theoretical interest to compare the influence of irrelevant size changes on visual versus haptic object recognition. In the present experiments we used the same method and well-controlled stimuli as Lawson (2009) used to examine the effects of orientation changes on unimodal and crossmodal visual and haptic object recognition.

6.1.1 Similarities between visual and haptic object recognition

The evidence that vision and haptics share representations based on geometric shape is compelling, yet the properties of this common perceptual representation, its relationship to unimodal representations, and its broader significance to object recognition are unclear. A key issue for models of object recognition has been to understand how we achieve object constancy by abstracting away from irrelevant variation in the input caused by changes in viewing position and lighting conditions (e.g. Biederman, 1987; Hummel & Stankiewicz, 1996; Riesenhuber & Poggio, 1999, 2002).

The effects of changes of orientation on visual object recognition have been the subject of much empirical research and debate (e.g. Biederman & Gerhardstein, 1993; Lawson, 1999; Hayward, 2003; Tarr & Bülthoff, 1995; Tarr & Cheng, 2003). Generally, the results of these studies and others indicate that visual object recognition is orientation-sensitive (see Peissig & Tarr, 2007, for a review). Recent behavioural research has found that haptic object recognition is also orientation-sensitive (Chapter 2; Craddock & Lawson, 2008; Lacey et al., 2007; Lacey, Pappas, Kreps, Lee, & Sathian, 2009; Lawson, 2009; Newell et al., 2001). All of these studies found broadly similar effects of orientation changes on unimodal visual and haptic object recognition which imply that similar orientation-sensitive representations are used by both modalities. If both modalities use orientation-sensitive representations, then information about orientation might be retained by an object representation which supports recognition across both vision and haptics. The orientation-sensitivity of crossmodal recognition has been tested directly. However, the results, as reviewed below, have been mixed.

Newell et al. (2001), using novel objects constructed from LEGO bricks, found that crossmodal visual-to-haptic (VH) and haptic-to-visual (HV) object recognition was orientation-sensitive. However, performance was better when objects were rotated by 180°

from study to test than when objects had the same orientation. This was the opposite pattern of orientation-sensitivity than that for unimodal recognition. They suggested that the surface which was perceived determined performance, and that the hands preferentially explored the rear of objects whereas the eye perceived the front of objects. Thus their results suggest that haptics and vision share common, perceptual representations, since performance was always better when the same surfaces were perceived, resulting in opposite directions of orientation-sensitivity between unimodal and crossmodal recognition.

However, Lacey et al. (2007) argued that Newell et al.'s results were an artefact of their stimuli. Newell et al.'s stimuli were elongated along their vertical, y-axis and haptic encoding of their near surface was relatively difficult given the biomechanical constraints of the hand. Thus, the ease of acquiring shape information from the near and far surfaces of the stimuli differed. Lacey et al. instead used stimuli which were elongated along their z-axis. Using a similar task to Newell et al., they found that crossmodal recognition was orientation-invariant irrespective of the direction of transfer. Lacey et al. argued that an abstract, high-level object representation underpins crossmodal recognition, and that this representation may be constructed from lower-level, unimodal, orientation-sensitive representations. Using the same stimuli, Lacey et al. (2009) used a perceptual learning paradigm, training with multiple orientations, to induce within-modal orientation-invariant performance. They found that this orientation-invariance then transferred completely across modalities: Once haptic orientation-invariance had been acquired, visual recognition was also orientation-invariant. They argued that this demonstrated that orientation information is not encoded in the representation underpinning crossmodal recognition.

This conclusion is not, though, consistent with the results reported by Lawson (2009), using the same sequential matching task and the same 3D plastic models of familiar objects as those used here. She found that visual-to-visual (VV), haptic-to-haptic (HH) and VH matching were all orientation-sensitive whereas HV matching was orientation-invariant. The presence of orientation-sensitivity in one direction (VH) but not the other (HV) indicates that crossmodal recognition is not fully orientation-invariant (cf. Lacey et al., 2007), but also that information may not be transferred symmetrically across modalities (cf. Newell et al., 2001).

Thus, while it is clear that there is an object representation accessible to both vision and haptics, it is unclear whether that representation is orientation-sensitive or orientation-invariant: The mixed results above could be attributed to differences in the tasks or stimulus sets employed by the various authors rather than reflecting true differences in its orientation-sensitivity. A more interesting possibility is that orientation may not be well matched across the two modalities. There is some evidence consistent with this proposal.

First, in her sequential shape matching task, Lawson (2009) manipulated shape discriminability as well as object orientation. She found that for VV matching the cost of ignoring orientation changes increased as the discrimination difficulty increased, whereas for HH and VH matching the cost of ignoring orientation changes was constant irrespective of discrimination difficulty. This suggests that the underlying cause of the orientation-sensitivity observed for VV matching might differ from that for matching involving haptic inputs. Second, Lacey et al. (2007) found that the axis of rotation was important for visual but not for haptic object recognition.

Therefore, an important caveat to conclusions drawn from studies which compare haptic and visual orientation-sensitivity is that it is not clear how well-matched changes of orientation are across modalities. The same 90° change in the orientation of an object may be perceived differently in the two modalities, since the mode of exploration differs markedly. For example, from a given viewpoint, vision can only acquire information from the front surface of an object, whereas haptic exploration can encompass most of a small object simultaneously without moving the body. In addition, different frames of reference may be used to encode object orientation visually versus haptically. If orientation is coded using a reference frame based on the sensor (the eye or the hand) then vision and haptics would encode different representations even if the same object was presented to a participant at a fixed position within the environment.

These differences make it harder to interpret patterns of orientation-sensitivity in unimodal and crossmodal visual-haptic experiments. We therefore decided to compare the achievement of object constancy across vision and haptics for a different but commonplace source of input variation: size changes. Different members of a given category often vary widely in size (for example, dogs, books). In addition, the retinal size of an object is a product not only of the object's physical size but also of its distance from the viewer, which the visual system must also compensate for.

6.1.2 Effects of size changes on visual and haptic object recognition

There has been substantial research into the effects of size changes on 2D visual object recognition, using line drawings of familiar or novel objects (Jolicoeur, 1987; Milliken & Jolicoeur, 1992; Srinivas, 1996), and greyscale (Biederman & Cooper, 1992; Fiser & Biederman, 1995) or colour (Uttl et al., 2007) photographs of familiar objects. These studies have shown that 2D visual object recognition is typically impaired by changes in size from study to test on old/new recognition or matching (though not on priming) tasks. In comparison, we are not aware of any studies of the effects of size changes on real, 3D visual object recognition and only our own on the haptic recognition of real, 3D objects (Chapter 5; Craddock & Lawson, 2009a). We will discuss this study in detail after briefly noting other haptic object recognition studies which have investigated size effects.

Studies using free- or directed-sorting tasks with 2D planar (Reed et al., 1990) or 3D cubes and spheres (Lederman et al., 1996) found that size was not a salient dimension for either vision or haptics. Furthermore, Lawson (2009) showed that people can recognise small-scale 3D models of familiar objects, indicating that haptics can generalise across unusual sizes.

In Chapter 5 (see also Craddock & Lawson, 2009a), we examined the effects of size changes on visual and haptic recognition of familiar 3D objects. Although Experiment 8 did not find a clear effect of size changes on priming of naming, in Experiment 9 size changes were similarly disruptive for both visual and haptic recognition in an old/new recognition task.

In Experiment 2 of Craddock & Lawson (2009a), participants performed a haptic sequential shape-matching task on 3D plastic models of familiar objects. Again there was a cost of ignoring irrelevant size changes: performance on match trials (such as when a car was followed by a car) was slower and less accurate when a small car was presented after a large car, or vice versa, than when the same-sized car was presented twice. These two experiments provided the first demonstration of a cost to generalising across size changes in haptics with 3D objects. The first experiment showed that these size change costs occur even when there are size-invariant cues such as texture or temperature available, since the stimuli were real, familiar objects. Furthermore, these size costs were comparable to those observed in vision.

If both vision and haptics use size-sensitive representations, then object representations that can be accessed by either modality may also be size-sensitive. This hypothesis was tested in the present studies. Given that an object's physical size is not contingent upon its spatial relationship to an observer, unlike an object's orientation, then if vision and haptics encode physical size similarly size changes should, in turn, be perceived similarly by both modalities. Furthermore, larger objects take longer to fully explore than smaller objects for both vision and haptics, and, although preferred size may differ, both modalities suffer from a lack of resolution as objects become smaller (Uttl et al., 2007;

Wijntjes et al., 2008). As a result it may be more informative to compare the effects of size changes to the effects of orientation changes when contrasting visual to haptic object recognition.

There were important limitations to our previous finding of similar size-sensitivity in visual and haptic object recognition. In Experiments 8 and 9 in Chapter 5, participants in the visual condition saw only 2D photographs of the familiar 3D objects rather than the actual objects, whereas participants in the haptic condition felt the actual objects. The photographs depicted the objects in a rich and consistent 3D context, and thus provided good information about the absolute size of the objects. This contrasts to most previous studies investigating the effects of size changes on visual object recognition, which have presented 2D images of 3D objects shown in isolation against a blank background without strong cues to their actual physical size or 3D location (Biederman & Cooper, 1992; Jolicoeur, 1987; Uttl et al., 2007). Nevertheless, the depth cues available in the visual and haptic conditions were not well matched in this study. Furthermore, the variation in the direction and magnitude of the size changes used in Chapter 5 was not controlled because real, everyday objects were presented.

We addressed these issues in two experiments which used a task-irrelevant size transformation to provide evidence about whether the same perceptual representations are used in visual and haptic object recognition. In Experiment 10, we compared unimodal VV matching with unimodal HH matching. Participants performed both VV and HH matching, and the same 3D objects were presented to each modality using the same apparatus, intermingled trials and matched timing. First, this tested whether there is a cost of generalising over visual size changes for 3D objects, an extension of the finding of a size-change cost for 2D photographs of 3D objects in Chapter 5. This has not previously been tested. Second, this allowed us to compare unimodal visual and haptic costs of size changes. In Experiment 11, we used the same task and stimuli as in Experiment 10 but participants performed crossmodal VH and HV matching. This provided a more direct test of whether the common representations involved in visual and haptic object recognition are size-sensitive.

6.2 Experiment 10

In Experiment 10, participants performed a sequential shape matching task using plastic, 3D models of familiar objects. The models were scaled to be approximately hand-sized, and were all made from the same, rigid, plastic. Thus, all the models had the same surface texture, temperature and compliance. Furthermore, the weight of the models bore little relation to the weight of the real exemplars of the modelled object category, although since participants were not allowed to pick up or move the objects weight was difficult for them to estimate. Thus, while participants could use most normal haptic exploratory procedures (Lederman & Klatzky, 1987, 1990), there were no non-shape cues to identity. The absence of non-shape cues should maximize the influence of our primary manipulation, changes in size, on participants' performance.

Participants studied an object for 5 seconds. They were then presented with either the same shaped object on match trials or a different shaped object on mismatch trials. On both match and mismatch trials, the first and second objects were the same size on half of the trials and were different sizes on the remaining trials. The task was to detect shape changes and ignore size changes. Both objects on a trial were presented to the same modality (i.e. trials were visual-to-visual, VV, or haptic-to-haptic, HH). Participants were informed about the modality of each upcoming trial using a verbal cue ("touch" or "look"). Based on the results in Chapter 5, we expected size changes to disrupt VV and HH matching about equally.

6.2.1 Method

Participants

Twenty-four students from the University of Liverpool participated in return for course credit. Ages ranged from 18 to 57, with most participants aged 18 or 19. Five participants were male, 19 female. Twenty-two participants were right-handed; two were left-handed.

Materials and Apparatus

The stimuli comprised a small and a large version of a startpoint morph and of an endpoint morph for each of 20 familiar object morph sets (see Lawson, 2009, and Craddock & Lawson, 2009a, for further details). The startpoint and endpoint morphs were similarly shaped objects but would normally be given different names, e.g., bath-sink, bed-chair and horse-giraffe. The small version of a given morph was 75% of the width, height and depth (so 42% of the volume) of the large versions. Note that for the majority of objects even the large version was considerably smaller than real life exemplars of the object, since all of the morphs could be comfortably grasped by one hand. All 80 stimuli (two sizes × two morphs × 20 morph sets) were 3D white rigid plastic shapes printed using a Dimension 3D ABS-plastic printer, see Figure 6.1.

Each morph was glued upright onto the centre of a 10cm square base made of carpet tile. Yellow tape marked the middle of one side of this base; the object was oriented so that its front was next to the yellow tape. The experimenter positioned objects by placing the base into a 10.5cm square hole cut into a surround made of a carpet tile. One side of this hole was marked with green tape. The yellow tape at the front of each object was always lined up with the green tape.

The object was hidden from the participant's view by card, a board, and a clouded glass screen. Behind and perpendicular to this glass screen was a 12cm square aperture through which the participant's right hand entered in order to touch the object on haptic trials or to begin each visual trial. An infra-red beam shone across this slot, placed so that it was broken when the participant's hand entered the slot. When this beam was broken a detector sent a signal to the computer controlling the experiment. Participants responded using a button box placed on the table in front of the glass screen and next to their left hand.

Design and Procedure

All participants completed one block of 80 trials comprising four sub-blocks of 20 trials. Across the full block of 80 trials there were two match trials and two mismatch trials for each morph set. One of each of these two trials presented both objects at the same size and the other trial presenting the second object at a different size. Both of the two mismatch trials presented the same distractor morph (once as the small and once as the larger version) as the second object. Half of the 80 trials presented both objects visually (VV trials) and half presented both objects haptically (HH). The two trial types were interleaved using an ABBA sequence.

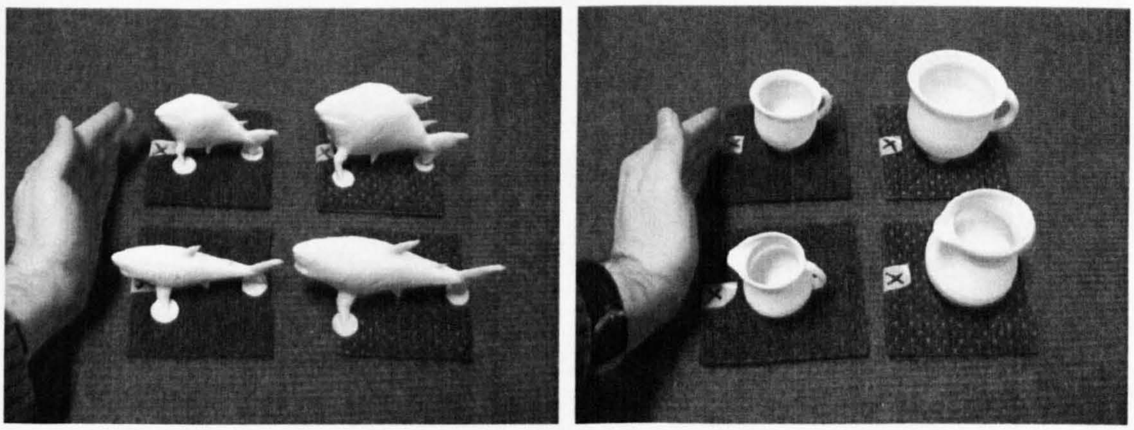

Figure 6.1. Examples of two sets (fish-shark and cup-jug) of the stimuli. Each photograph shows the small exemplars on the left and large exemplars on the right.

One group of ten morph sets was presented on 40 of the trials in a block. The other group of ten morphs sets was presented on the remaining 40 trials. For half of the participants, the first object presented on a given trial was the startpoint morph (e.g. bath) if it was from the first group of ten morph sets and the endpoint morph (e.g. sink) if it was from the second group of ten morph sets. This assignment was reversed for the remaining participants. On match trials, the second object presented was the same startpoint or endpoint morph as the first object. On mismatches, the second object presented was the startpoint morph if the endpoint morph had been presented first, or the endpoint morph if the startpoint morph had been presented first. Note that this design ensured that the matching task was quite difficult, since only objects with related shapes (such as a shark then a fish or a cup then a jug, see Figure 6.1), were presented on mismatch trials. The order of trials in each sub-block was fixed and an equal number of participants in each condition received the forward and reversed version of this order. Also in each condition, one participant received the trials using the sequence HH-VV-VV-HH, while a second participant received the same sequence of trials using the sequence VV-HH-HH-VV.

The experiment was run on a computer using E-Prime version 1.1 experimental presentation software (Psychology Software Tools Inc., Pittsburgh, PA). At the start of each trial, the experimenter placed the first object into position behind the screen then triggered the computer to play the word "look" on VV trials or the word "touch" on HH trials. This signalled to the participant that they could start to move their right hand through the aperture. The computer recorded when their hand broke the infrared beam across the slot. On VV trials, the screen cleared 500ms after the beam was broken. This 500ms delay compensated for the extra time after breaking the beam for participants to move their hand to the object in the HH condition. The screen then clouded 4500ms after it had cleared. On VV trials they stopped moving their right hand once the beam was broken so their hand did not go near to the object. On HH trials, the screen remained opaque throughout but their right hand could explore the object for five seconds. Five seconds after the beam was broken the words "stop now" were played by the computer, signalling that the participant should withdraw their hand from the slot. The experimenter then removed the first object and either put the same object back behind the screen on match trials or replaced it with a different object on mismatch trials. The experimenter then triggered the computer to play the word "look" or "touch", and the participant put their hand back through the aperture. In both conditions, the trial concluded when the participant responded, with the screen remaining clear until that time during VV trials and remaining opaque throughout on HH trials.

Participants decided whether the two successively presented objects had the same shape and responded with a speeded keypress. The computer recorded the time from when their right hand broke the infrared beam until they responded with their left hand by pressing one of two buttons (marked "same" and "different") on a response button box. People were told to ignore any difference in the size of the first and second objects. They were also warned that on mismatches the two objects might have very similar shapes. After they had responded, they heard either a high or a low double tone as feedback which indicated a correct or incorrect response respectively. Participants completed a block of ten practice trials prior to starting the experimental block. These trials were identical to the final ten experimental trials.

After the first object had been presented it was always removed from the apparatus. A second object (the distractor on mismatches and an object from the same morph set as the first object on matches) was then taken from the storage shelf and placed next to the first object. Finally, one of these two objects was put into the apparatus as the second object on a trial. This procedure ensured that participants could not determine whether they were going to be given a match or a mismatch trial from the movements or sounds made by the experimenter. At the end of the study, participants were asked whether they had only used haptic information in the haptic condition to make their responses, or if they had also used auditory or visual information, such as the sounds of the experimenter moving objects or seeing the objects. None reported the use of information other than that gathered by touching or seeing the objects as appropriate.

6.2.2 Results

Mixed analyses of variance (ANOVA) were conducted on mean correct reaction times (RTs) and mean percentage errors for matches and mismatches separately. On matches, same-shape responses were correct. On mismatches, different-shape responses were correct. Reaction times shorter than 350ms or longer than 5000ms on VV trials and shorter than 750ms or longer than 10000ms on HH trials were discarded as errors (less than 1% of trials). No participants were replaced. Size (same or different) and modality (VV or HH) were used as within-participants variables. Subscripts F_p and F_i denote by-participants and by-items analyses F-values respectively.

Same-shape matches

Size was significant for RTs [$F_p(1,23) = 28.004, p < .001$; $F_i(1,19) = 48.234, p < .001$] and errors [$F_p(1,23) = 22.821, p < .001$; $F_i(1,19) = 36.782, p < .001$]. Matching on same-size trials (1945ms; 3%) was 210ms faster and 11% more accurate than matching on different-size trials (2155ms; 14%). There was therefore a substantial cost of generalising over size changes on both the speed and accuracy of performance.

Modality was significant for RTs [$F_p(1,23) = 450.292, p < .001$; $F_i(1,19) = 986.128, p < .001$] and errors [$F_p(1,23) = 22.594, p < .001$; $F_i(1,19) = 7.472, p = .013$]. VV matching

(1163ms; 5% errors) was 1774ms faster and 7% more accurate than HH matching (2937ms; 12%).

There was no size × modality interaction for RTs [$F_p(1,23) = 1.043$, $p = .3$, see Figure 6.2a; $F_i(1, 19) = .666$, $p = .4$], but there was a marginal interaction for errors [$F_p(1,23) = 4.136$, $p = .05$, see Figure 6.2b; $F_i(1,19) = 4.125$, $p = .06$]. On VV trials, same-size matching was 238ms faster and 8% more accurate. On HH trials, same-size matching was 183ms faster and 15% more accurate.

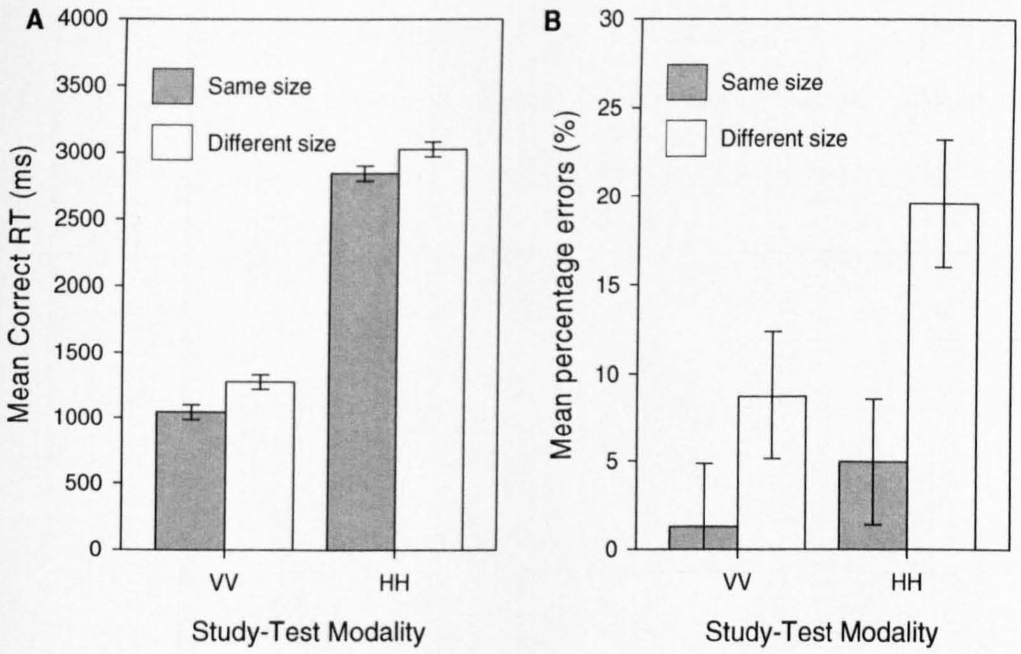

Figure 6.2. (a) Mean correct RTs (ms) and (b) mean percentage errors for unimodal, visual-to-visual (VV) and haptic-to-haptic (HH) matches in Experiment 10. Error bars show 95% within-participant confidence intervals calculated using the error term of the modality × size interaction (see Loftus & Masson, 1994; Jarmasz & Hollands, 2009).

Different-shape mismatches

Mismatch trials were not the focus of this study since they presented two different shaped objects (e.g., frog then lizard). This shape change often produced a substantial size change in at least one dimension (for example, the lizard was much longer than the frog). It is therefore difficult to interpret the results of mismatches in terms of the effects of the size-change manipulations. Nevertheless, the mismatch results are presented here for completeness.

Size was not significant for RTs [$F_p(1,23) = .008, p = .9$; $F_i(1,19) = .436, p = .5$] or errors [$F_p(1,23) = .008, p = .9$; $F_i(1,19) = .014, p = .9$]. Modality was significant for RTs [$F_p(1,23) = 267.690, p < .001$; $F_i(1,19) = 641.978, p < .001$] and errors [$F_p(1,23) = 35.276, p < .001$; $F_i(1,19) = 19.301, p < .001$]. VV mismatches (1162ms; 4%) were 1868ms faster and 19% more accurate than HH mismatches (3030ms; 23%). There was no size x modality interaction for RTs [$F_p(1,23) = .358, p = .6$; $F_i(1,19) = .013, p = .9$] or errors [$F_p(1,23) = .015, p = .9$; $F_i(1,19) = .041, p = .8$].

6.2.3 Discussion

The results were clear: for both vision and haptics, sequential shape matching was performed faster and more accurately when a given object was presented both times at the same size compared to when it changed size from the first to the second presentation.

These results are the first demonstration of size change costs to visual recognition using 3D objects. The majority of previous research investigating visual size change effects presented photographs or line drawings of objects set against blank backgrounds with no environmental context. Here, size changes could either be interpreted as changes of distance or as attributable to rescaling of an image. In Chapter 5, size change effects occurred even when the photographs show objects within a standard scene which provided good information about physical object size. The current study extended this result by presenting 3D objects with full, consistent cues to actual size and presented at a fixed distance. Here, differences in size would have been seen as changes in the physical size of an object and yet size change costs were still observed.

There was also a substantial cost of size changes for haptic recognition. It was therefore clear that both vision and haptics used size-sensitive representations of shape to perform the task. Experiment 10 used the same task, the same apparatus and a within-participant manipulation of modality and the cost on RTs of compensating for size changes was similar for visual and haptic recognition. This finding is consistent with the claim that, notwithstanding the differences between initial sensory processing across the two modalities, subsequent stages of perceptual object processing are similar for vision and touch.

Contrary to the predictions of this claim, there was a marginal interaction between size change and modality for errors, indicating that the absolute size change cost was somewhat smaller for vision than for haptics. However, as Figures 6.2a and 6.2b show, VV matching was also much faster and more accurate overall than HH matching. Our analysis of absolute costs may therefore have underestimated the size cost for VV matching. In contrast, when comparing relative costs, VV size changes increased RTs by 23% and errors by 600%, whilst HH size changes increased RTs by 6% and errors by 292%. There may also have been a ceiling effect for errors in the same-size VV condition, see Figure 6.2b.

These differences in baseline performance across the modalities are an inevitable consequence of the fundamental differences between normal processing by vision and haptics, such as the rate and means of acquisition of shape information. Overall levels of performance can usually only be equated across the modalities by artificially constraining information acquisition, for example by restricting vision to a narrow field of view (Loomis et al., 1991). An alternative approach was used in Experiment 11: Crossmodal matching was investigated. If size-sensitivity is weaker for visually compared to haptically encoded representations then there should be a reduced cost for VH size changes than for HV size changes.

Importantly, testing crossmodal as well as unimodal matching permits a comparison of size-sensitivity across trials with similar baseline performance, since the modality to which the second object presented is the main determinant of overall performance. Specifically, VV and HV performance are similarly fast whereas HH and VH performance are similarly slow (e.g. Craddock & Lawson, 2009a). A cross-experiment analysis is presented below, after the results of Experiment 11 have been reported.

6.3 Experiment 11

The results of Experiment 10 suggested that the cost of size changes was similar for VV and HH matching, consistent with an account of object recognition in which vision and haptics share the same or similar perceptual representations. These results are also similar to those observed by Lawson (2009) for VV and HH matching across orientation changes using the same task, stimuli and apparatus. However, as Lawson (2009) demonstrated, this superficial similarity needs to be investigated further since important differences in orientation-sensitivity have also been observed between the two modalities for crossmodal matching and when another factor, shape discriminability, is manipulated. Therefore in Experiment 11, we used the same sequential shape matching task as in Experiment 10 to test crossmodal visual-to-haptic (VH) and haptic-to-visual (HV) matching.

The results of Experiment 10 suggested that both visual and haptic encoding produces size-sensitive representations. Any representation mediating crossmodal recognition may therefore also be size-sensitive. Alternatively, if crossmodal matching is mediated by a more abstract shape representation (Lacey et al., 2007), then there should be no cost of size changes to crossmodal shape matching. Furthermore, any difference in the size-sensitivity of representations encoded visually versus haptically should modulate size change costs according to the direction of transfer. If visual representations are less size-sensitive than haptic representations, the cost of size changes should be reduced for VH compared to HV matching.

6.3.1 Method

Participants

Twenty-four students from the University of Liverpool participated in return for course credit. Ages ranged from 18 to 26. Twenty-two were right-handed, two left-handed. Three were male, 21 female.

Design and procedure

Experiment 11 was identical to Experiment 10 except that the two objects on each trial were presented to different modalities. If the first object was presented visually, then the second object was presented haptically and vice versa. Half of the trials presented the first object visually and the second object haptically (VH trials), and half presented the first object haptically and the second object visually (HV trials). Trials were ordered using the same ABBA design as in Experiment 11, with VH trials replacing VV trials and HV trials replacing HH trials.

6.3.2 Results

Mixed ANOVAs were conducted on mean correct reaction times and mean percentage errors for matches and mismatches separately. On matches, same-shape responses were correct. On mismatches, different-shape responses were correct. Reaction times shorter than 350ms or longer than 5000ms on HV trials and shorter than 750ms or longer than 10000ms on VH trials were discarded as errors (less than 1% of trials). Three participants were replaced as they made errors on over 30% of trials. Size (same or different) and modality (VH or HV) were used as within-participants variables.

Same-shape matches

Size was significant for RTs [$F_p(1,23) = 12.334$, $p = .002$; $F_i(1,19) = 26.922$, $p < .001$] and for errors [$F_p(1,23) = 17.040$, $p < .001$; $F_i(1,19) = 40.619$, $p < .001$]. Same-size matches (2464ms; 9%) were 243ms faster and 11% more accurate than different-size matches (2707ms; 20%). There was a substantial cost of generalising over size changes on both the speed and accuracy of performance.

Modality was significant for RTs [$F_p(1,23) = 247.283$, $p < .001$; $F_i(1,19) = 377.671$, $p < .001$] and for errors [$F_p(1,23) = 8.144$, $p = .009$; $F_i(1,19) = 7.715$, $p = .01$]. HV matching (1535ms; 18% errors) was 2100ms faster but 8% less accurate than VH matching (3635ms; 10%).

The size × modality interaction was significant for RTs [$F_p(1,23) = 4.484$, $p = .05$, see Figure 6.3a; $F_i(1,19) = 6.591$, $p = .02$] but not for errors [$F_p(1,23) = 1.275$, $p = .3$, see Figure 6.3b; $F_i(1,19) = .941$, $p = .3$]. On HV trials, same-size matches were 109ms faster and 13% more accurate than different-size matches. On VH trials, same-size matches were 377ms faster and 9% more accurate than different-size matches.

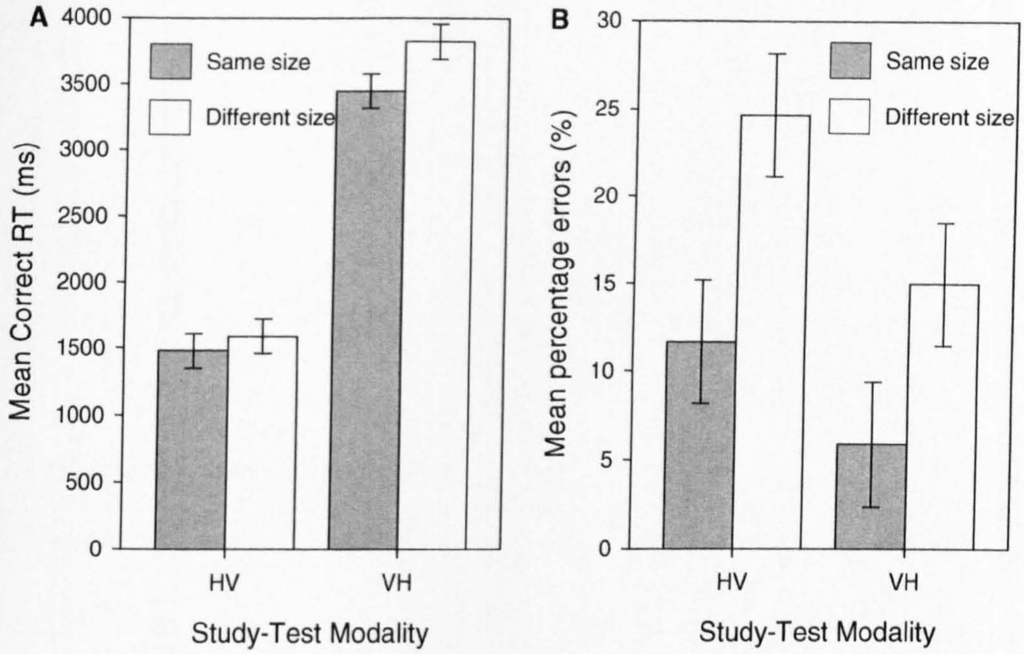

Figure 6.3. (a) Mean correct RTs (ms) and (b) mean percentage errors (%) for crossmodal, haptic-to-visual (HV) and visual-to-haptic (VH) matches in Experiment 2. Error bars show 95% within-participant confidence intervals calculated using the error term of the modality × size interaction (see Loftus & Masson, 1994; Jarmasz & Hollands, 2009).

Different-shape mismatches

As in Experiment 10, it is difficult to interpret performance on mismatch trials since the shape changes also often produced substantial size changes. Nevertheless, as before, the results are presented here for completeness. There was a weak trend of size for RTs [$F_p(1,23) = 3.506, p = .07; F_i(1,19) = 3.070, p = .1$] and for errors [$F_p(1,23) = 3.036, p = .1; F_i(1,19) = 1.423, p = .2$]. Same-size mismatches (2703ms; 23%) were 148ms slower and 4% less accurate than different-size mismatches (2591ms; 19%). Modality was significant for RTs [$F_p(1,23) = 300.566, p < .001; F_i(1,19) = 240.682, p < .001$] but not errors [$F_p(1,23) = 1.324, p = .3; F_i(1,19) = 1.929, p = .2$]. HV mismatches (1580ms; 22%) were 2134ms faster than

VH mismatches (3714ms; 25%). There was no size x modality interaction for RTs [$F_p(1,23) = .784, p = .4$; $F_i(1,19) = 2.713, p = .1$] or errors [$F_p(1,23) = .395, p = .5$; $F_i(1,19) = .503, p = .5$].

6.3.3 Discussion

For both HV and VH crossmodal matches, there was a cost of ignoring irrelevant size changes. This extended the results of Experiment 10 which found size change costs for both VV and HH unimodal matches. The results indicate that crossmodal object recognition depends at least partly on size-specific, perceptual representations rather than solely on more abstract shape representations (Lacey et al., 2007).

There was no interaction between transfer direction (VH or HV) and the cost of size changes for errors, consistent with the hypothesis that similar object representations were accessed in both cases. However, for reaction times the size cost was larger for VH compared to HV matching. Importantly, though, this difference suggests that now visually-encoded representations were more size-sensitive than haptically-encoded representations, so this effect was in the opposite direction to that found in Experiment 10. This in turn suggests that the reason for the variation in size-sensitivity in both studies is that size-sensitivity is greater when overall responses are slower due to the second object being presented haptically, on VH and HH trials, compared to when the second object is presented visually, on HV and VV trials. Size changes increased RTs by 11% in VH matching and 7% in HV matching, so the relative increase in RTs was similar in both cases.

Comparing size change costs for unimodal and crossmodal matching

To simplify the presentation of this data, and since the size change cost was the main measure of interest, we subtracted the RTs and errors for same-size trials from RTs and errors for different-size trials for all conditions. We then performed a mixed ANOVA on this mean size change cost for RTs and errors using second object modality (visual for VV and HV matches or haptic for HH and VH matches) as a within-participants factor and transfer (unimodal for VV and HH matches or crossmodal for HV and VH matches) as a between-participants factor.

There was a non-significant trend of second object modality for RTs [$F_p(1,46) = 2.174$, $p = .1$; $F_i(1,19) = 2.241$, $p = .2$], with smaller costs (179ms) on VV and HV trials than on HH and VH trials (281ms), but no effect for errors [$F_p(1,46) = .443$, $p = .5$; $F_i(1,19) = .313$, $p = .6$].

There was no effect of transfer for either RTs [$F_p(1,46) = .108$, $p = .7$; $F_i(1,19) = .044$, $p = .8$] or errors [$F_p(1,46) = .000$, $p = 1$; $F_i(1,19) = .008$, $p = .9$].

There was an interaction between second object modality and transfer for both RTs [$F_p(1,46) = 5.732$, $p = .02$, see Figure 6.4a; $F_i(1,19) = 7.524$, $p = .01$] and errors, though only marginally by-items [$F_p(1,46) = 5.035$, $p = .03$, see Figure 6.4b; $F_i(1,19) = 3.712$, $p = .07$]. We conducted post-hoc Tukey's HSD tests on these interactions. For RTs, there was a greater size cost to VH matching than to HH or HV matching. For errors, the size cost was greater for HH matching than for VV matching. No other comparisons were significant.

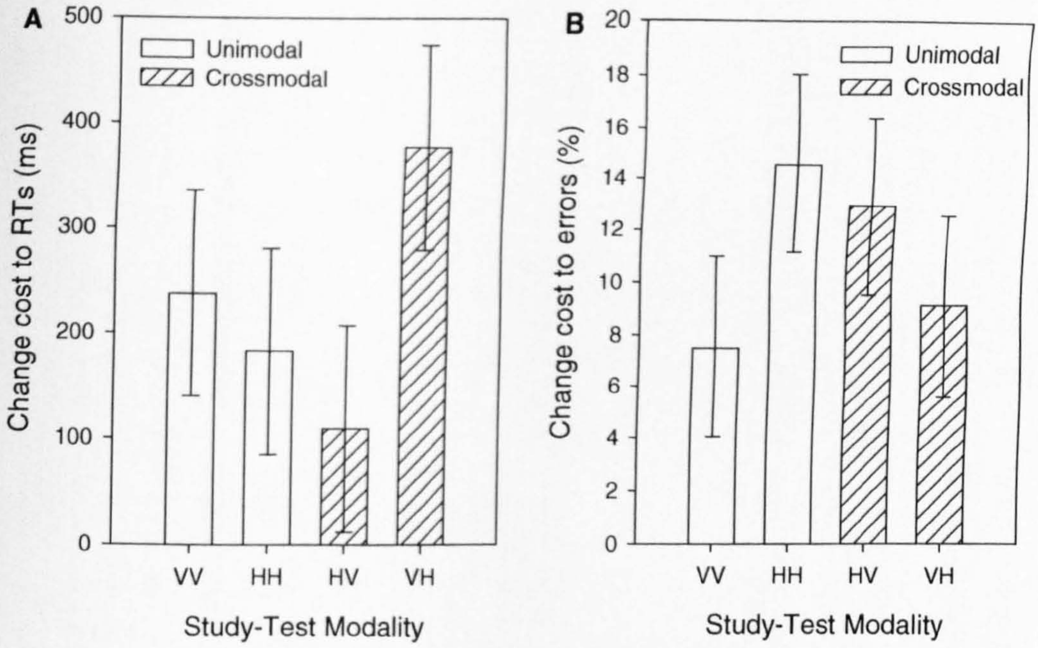

Figure 6.4. Size change cost to (a) mean correct RTs (ms) and (b) mean percentage errors (%) in Experiment 11 (VV and HH matching) and Experiment 12 (HV and VH matching). Clear bars represent unimodal matching, hatched bars crossmodal matching. White bars represent trials with visual second objects, grey bars with haptic second objects. Error bars show 95% within-participant confidence intervals calculated using the error term of the second object modality × transfer interaction (see Loftus & Masson, 1994; Jarmasz & Hollands, 2009).

The above analysis of size costs did not permit a comparison of overall performance on crossmodal versus unimodal matches because only differences in performance were analysed. Since this comparison is of theoretical interest, we also compared the results of Experiment 10 and Experiment 11 directly using the same factors as in those separate experiments but with the addition of transfer (unimodal or crossmodal) as a between-participants factor. Crossmodal matching (2585ms, 14%) was 535ms slower [$F_p(1,46)$ =

18.099, $p < .001$; $F_i(1,19) = 182.349$, $p < .001$] and 5% less accurate [$F_p(1,46) = 9.249$, $p = .004$; $F_i(1,19) = 7.730$, $p = .012$] than unimodal matching (2050ms, 9%).

Discussion of cross-experiment analyses

We compared unimodal to crossmodal matching directly by analysing the results of Experiments 10 and 11 together. This revealed a modest decrease in speed and accuracy for crossmodal matching, consistent with previous findings of a cost of transfer across modalities (e.g. Lacey, et al., 2007; Norman et al., 2004).

The analysis of size change costs revealed an interaction between second object modality and transfer. This interaction might be taken as evidence against the hypothesis that the same perceptual representations are involved in visual and haptic object processing. However, the larger size cost on errors for HH compared to VV matches is likely due to differences in overall accuracy across these two conditions, with fewer errors made on VV matches, see Figure 6.2. Similarly, the larger size costs to RTs for VH than for HV or HH matching may at least in part be due to this condition being the slowest overall. Furthermore, this condition did not produce the largest size costs for errors, see Figure 6.4b. The modest differences in size change costs across the four conditions appear to mainly reflect variation in overall levels of performance rather than the effects of modality per se. It is also important to note that there were significant size costs in all conditions, and there were no differences between size costs in the unimodal and crossmodal conditions.

6.4 General discussion

Together the two studies reported here tested unimodal (HH and VV) and crossmodal (HV and VH) sequential matching of 3D models of familiar objects. In all four conditions performance was better on same-size relative to size change matches, indicating that the perceptual shape representations underlying visual and haptic object recognition are size-sensitive. These results extend our previous findings of size-sensitivity in 2D visual and 3D haptic object recognition (Chapter 5; Craddock & Lawson, 2009a).

The size costs found for VV matches are consistent with previous findings of effects of size changes on 2D images (Biederman & Cooper, 1992; Craddock & Lawson, 2009a; Fiser & Biederman, 1995; Jolicoeur, 1987; Milliken & Jolicoeur, 1992; Srinivas, 1996; Uttl et al., 2007) and extend them to an ecologically important situation in which participants saw real 3D objects in a rich and consistent context with full depth cues. There were similar size costs for HH matches, providing evidence that the same representations are involved in visual and haptic object recognition.

However, research investigating the effects of orientation transformations on visual versus haptic object recognition has shown that superficial similarities in unimodal performance across the two modalities may be misleading. More fine-grained investigation may reveal important differences between the modalities. For example, Lawson (2009) found that an additional factor, discrimination difficulty, had different effects on visual versus haptic matching, and crossmodal transfer was orientation-sensitive from vision to haptics but orientation-invariant from haptics to vision (see also Jüttner, Müller, & Rentschler, 2006). Furthermore, VH and HV crossmodal transfer has also been reported to be orientation-sensitive in both directions (Newell et al., 2001) and orientation-invariant in both directions (Lacey et al., 2007). However, note that Newell et al.'s results may not generalise beyond the particular stimuli and orientations that they used, whilst in both crossmodal conditions in Lacey et al. (2007) there was a trend towards a same-orientation advantage to recognition. Thus, their finding of orientation-invariance may have been due to a lack of statistical power.

Given the difficulty in interpreting these varying results for crossmodal recognition, the present findings provide important evidence about the achievement of object constancy for haptics versus vision by manipulating size rather than orientation changes. Lawson (2009) investigated crossmodal matching using the same task, stimuli and apparatus as in the present studies. Experiment 11 here was motivated by her finding of asymmetrical crossmodal transfer effects on orientation sensitivity for VH compared to HV matching. Despite the similarity between these two studies, a different pattern of results was found to that observed by Lawson (2009), with size change costs observed for both VH and HV matches.

Our results confirm that both visual and haptic object recognition employ size-sensitive representations, and indicate that each can efficiently access size-specific representations encoded by the other modality. These object representations preserve task-irrelevant perceptual information about a specific encounter with a given object, so are not abstract representations of shape (Lacey et al., 2007; Lacey, Pappas et al., 2009) or semantic or verbal representations. We suggest that the variation in results for the achievement of object constancy across previous studies may be due to the difficulty in equating object transformations such as orientation across vision and haptics. This difficulty arises from the fundamental differences between the modalities, for example in the amount of the surface of an object that can be explored simultaneously or from a given position and because vision and haptics may encode objects using different frames of reference. Relative to orientation changes, we propose that size transformations provide an important alternative - and arguably superior - means of comparing visual to haptic object recognition.

CHAPTER 7| General Discussion

Haptic object recognition is remarkably fast and capable at identifying real familiar objects. The evidence presented in this thesis shows that haptic object recognition displays remarkable similarity to visual object recognition, consistent with the suggestion that the two modalities share representations and object recognition mechanisms. These similarities range from maintaining object constancy over orientation changes to generalizing across size changes. We have demonstrated these similarities using several different tasks and a range of both of familiar and unfamiliar stimuli, providing compelling evidence that the effects we have found are robust and unlikely to be artefacts of a particular experimental design or particular set of objects.

7.1 Haptic orientation-sensitivity

Investigations of haptic susceptibility to orientation changes proved a fruitful approach. Firstly, haptic recognition is similarly susceptible to orientation changes as is vision. In Chapter 2, we demonstrated that the orientation effects which had previously been observed in haptic recognition of novel objects (Newell et al., 2001) also extended to haptic recognition of familiar objects. Experiment 1 examined priming of naming, and, while we found significant haptic priming, we found no effect of orientation changes on that priming. Nevertheless, we did find an effect of initial orientation on naming speed and accuracy: objects were recognised faster and more accurately in some orientations than in others. We interpreted this as support for the existence of canonical orientations in haptic object recognition analogous to visually canonical orientations (Palmer et al., 1981). This was subsequently corroborated by Woods, Moore, and Newell (2008), who also found evidence that objects were easier to recognise haptically in some orientations than others.

We conducted three further experiments on the theme, examining possible explanations for the absence of effects of orientation on priming. If participants were simply not storing the objects' orientations, or if the priming we observed was purely name or semantic priming, then no effects of orientation would be possible. Experiment 2 showed that participants were very good at remembering the orientation in which the object was placed, contrary to the first explanation; Experiment 3 showed that when objects were visually rather than haptically primed before haptic recognition, and thus priming was crossmodal rather than unimodal, priming was reduced. Thus, a component of haptic priming is specifically perceptual, since both visual and semantic priming could have accounted for the improvement in naming speed seen for visually primed objects.

This lead to another alternative explanation: that priming of naming, as an implicit task, lacked sufficient sensitivity to reliably detect effects of orientation. We tested old/new recognition of both familiar and unfamiliar objects, and found a cost of orientation changes to recognition speed and accuracy for both types of object. The use of unfamiliar objects may have forced participants to rely on more perceptual than semantic representations, given that they would have no existing representations of unfamiliar objects, thus maximising orientation-sensitivity.

Chapter 3 confirmed our initial findings of haptic orientation sensitivity using a different set of stimuli and a different task. We showed that the orientation-sensitive representations haptics uses to perform sequential shape matching are maintained over 15s, longer than has been documented in similar visual tasks. This may be because haptics explores objects in a slower, more sequential fashion than does vision. Having to integrate information from across multiple fingertips following multiple movements may mean that haptics makes greater use of shorter-term memory to build up a representation of an object.

In Chapter 4, we examined the effect of exploration hand on recognition of familiar objects, and extended the work on orientation-sensitivity by examining how orientation might interact with the exploration hand. We suggested that advantages in object identification might be found with the preferred hand for two reasons: greater manual expertise with the preferred hand; more familiarity with objects with the preferred hand. The objects were presented in either left or right hand graspable orientations. For example, an object placed with its handle pointing towards the right hand should be more easily graspable for the right hand than the left. We found that naming was unaffected by the hand used to explore objects. Thus, neither manual expertise nor familiarity influenced haptic object identification.

Furthermore, exploration hand did not interact with the orientation of objects, suggesting that the mechanisms underpinning identification and grasping may differ. We also found that priming was unaffected by changes of exploration hand, changes of orientation, or any combination of the two. To explore reasons for this null result, we repeated the experiment but asked participants to remember whether they had touched the objects with the same hand or in the same orientation. Although participants could remember both the exploration hand and the orientation, they were better at remembering the orientation than the hand, suggesting that orientation forms a more salient part of the perceptual representation.

At the end of Part I, I highlighted the difficulty of comparing the effects of manipulations of orientation across modalities. As discussed in Part II, attempts to examine the effects of changes of orientation across the visual and haptic modalities had previously provided mixed results, and it is not clear how similar visual views and what constitutes haptic "views" are. I argued that size might prove a characteristic of objects that would be easier to match across modalities and thus, may yield more informative results.

7.2 Haptic size-sensitivity

In Chapter 5, we examined the effects of changes of size on haptic recognition using real familiar objects, and directly compared visual performance on a similar task. We predicted that size changes may disrupt haptic recognition more than they may disrupt visual recognition. In Experiment 8, participants named one of three different exemplars of familiar objects: a standard size and shape exemplar, a different size but similar shape exemplar, or a different shape but similar size exemplar, then named the standard size and shape exemplar of each object in a second block. The use of a more explicit measure of old/new recognition in the Experiment 9 in Chapter 5 yielded clearer results. We found that both visual and haptic recognition exhibited surprisingly similar patterns of performance, with an advantage to old/new recognition when objects did not change size or shape from study to test.

There were a number of disadvantages to the methods used in Chapter 5. First, since we used real, familiar objects, the direction and magnitude of the size changes we employed was somewhat variable. Sometimes the different size object was smaller, whereas sometimes it was larger. Sometimes the difference in size was substantial, whereas sometimes it was relatively small. Second, there were some differences in the presentations: whereas on haptic trials the real 3D objects were presented, on visual trials 2D photographs of the real objects were presented. Furthermore, there was no crossmodal, visual-haptic or haptic-visual testing. Thus, despite the similarities that were found, it was not possible to say whether they were because the two modalities were using the same representations, or were simply using comparable modality-specific representation.

These problems were corrected in Chapter 6. We used a sequential shape-matching task using different sized pairs of models of familiar objects. The amount of size change for these models was precisely controlled, with the smaller model being 75% of the size (by volume) of the larger model. Firstly, the findings of Chapter 5 were replicated despite the change of task and change of stimuli, with comparable effects of size changes for both vision and for haptics. Secondly, crossmodal matching was also sensitive to changes in size. Importantly, the cost of size changes was remarkably similar across all of the unimodal and crossmodal conditions, indicating that the representations which underpin crossmodal recognition do code size and are perceptual rather than fully abstract. This was a particularly important result given that previous studies investigating the effects of orientation changes on crossmodal object recognition had yielded such mixed results (Lacey et al., 2007; Lawson, 2009; Newell et al., 2001).

7.3 Towards a multisensory account of haptic and visual object recognition

As discussed in the introduction, considerable process has been made since the early attempts to formulate models of haptic object recognition. There is now a far fuller picture of the underlying neural architecture of both visual and haptic object recognition and a substantial body of behavioural evidence in both modalities. The original models of haptic object recognition were *image-mediation* and *direct-apprehension* (Klatzky & Lederman, 1987). Under *image-mediation,* haptic object recognition is almost entirely the same as visual object recognition; haptic input is converted into a visual image which is processed and interpreted by the visual system, with no haptic specific processing. Under *direct-apprehension*, the haptic system has its own physiological apparatus for achieving object recognition, and only begins to share resources and representations with vision at a relatively high-level. Neither of these models was entirely correct, but neither was either model entirely wrong.

It is clear from neuroimaging evidence that there is substantial involvement of what would traditionally be considered visual cortex in haptic object recognition tasks (e.g. the LOC – see Amedi et al., 2001, 2002, 2005), and that some of this activity may be explicable by visual imagery (Deshpande et al., 2010; Lacey et al., 2010). Nevertheless, similar activity also occurs in the blind (Pietrini et al., 2004), for whom a visual imagery explanation seems implausible. Furthermore, Deshpande et al., (2008) found that a substantial amount of the activation in visual cortex during haptic object exploration could be explained by direct input from primary somatosensory cortex. Yau et al. (2009) identified areas in visual and somatosensory cortices that respond similarly to particular low-level fragments of object shapes. Thus, both vision and touch have their own, modality-specific areas that respond to comparable perceptual input, and these areas occupy an intermediate processing stage in their respective physiological hierarchies. Both of these areas have connections to the same area in visual cortex, the LOC, suggesting vision and haptics use a common format to process 3D shape.

Thus, the most parsimonious account is a multisensory model of object recognition of the kind described by Lacey, Tal et al. (2009), in which the two modalities share a common, multisensory representation of shape. Note that this does not imply full perceptual equivalence between representations derived from either modality. Clearly, there are some characteristics of objects which are imperceptible to one modality but perceptible to another. For example, colour is imperceptible to touch but perceptible to vision. Furthermore, as Philips, Egan, and Berry (2009) discovered, the perceptual equivalence between representations derived from vision and haptics depends somewhat on stimulus complexity: haptics becomes less capable of discriminating between objects as they become more complex. Nevertheless, the evidence presented in this thesis makes a substantial contribution to our current understanding both of haptic object recognition and of this multisensory object representation.

Some authors have argued that the multisensory representation of objects is built from multiple orientation-sensitive unimodal visual and haptic representations, and thus is orientation-independent (Lacey, Pappas, et al., 2009). As discussed in Chapter 6, the evidence on this point is contradictory, with some experiments finding orientation-sensitivity in both directions (Newell et al., 2001) or one direction (Lawson, 2009) of crossmodal visuo-haptic transfer, and only one study finding complete crossmodal orientation-invariance (Lacey et al., 2007). A fundamental problem with Lacey, Pappas et al.'s (2009) argument is that a multisensory object representation derived from a single, orientation-sensitive unimodal representation must therefore also be orientation-sensitive, and a collection of multiple orientation-sensitive multisensory representations would also explain any orientation-invariance. Furthermore, the great similarity between vision and haptics in generalizing recognition of objects across orientation changes, as evidenced in Chapters 2 to 4, makes this extra layer of orientation-dependent unimodal representations seem unnecessary when a single layer of orientation-dependent multisensory representations could also explain the results. This does not imply that are no unimodal representations, but simply that orientation-sensitivity is not sufficient to distinguish between unimodal and multisensory representations.

The mixed results discussed above may be due to the complexity of matching visual and haptic orientations. Newell et al. (2001) highlights this difficulty: they found that crossmodal matching was orientation-sensitive objects were rotated back-to-front between study and test. Thus, even though the object was studied in the same orientation relative to the trunk of the observer in either modality, this resulted in a somewhat different orientation-sensitivity in the other modality, implying that the two may use somewhat different reference frames for encoding orientation.

By testing for effects of size changes, we hoped to circumvent this problem. Orientation depends on the specific spatial relationship between the observer and the observed, and thus is not an intrinsic property of the object. Size, however, is an intrinsic property of an object; although an object's retinal size depends upon the spatial relationship between the observer and the object, its physical size does not. The results in Chapters 5 and 6 showed that size-change costs are comparable in both unimodal and crossmodal settings. Therefore, only a single, multisensory size-specific representation is necessary to account for these findings.

The results presented in this thesis are compatible with an account of visual and haptic recognition in which both modalities generate size- and orientation-sensitive multisensory representations. Therefore, crossmodal object recognition can be accomplished through the use of relatively low-level, perceptual representations, rather than only through high-level, abstract representations such as names or other semantic labels. Note that this model deals primarily with the perceptual process of object recognition: the generation of object representations based on physical characteristics that can be matched to stored representations of those same objects. Future research might be directed at examining the use of higher-level representations in haptic recognition.

To return to the original starting point for this thesis, a comparison of the mechanisms of object constancy in vision and haptics, this model and the results presented here suggest that, faced with the task of overcoming similar problems in both modalities, such as compensating for changes in object orientation or object size, the brain may have reached a particularly efficient solution: To use the same mechanisms and neural areas to deal with a specific task which has many commonalities in both modalities, despite the differences in the perceptual input received from the hand and the eye.

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APPENDIX I|

Object names for the familiar items used in Chapter 2, Experiments 1 to 4, alternative names accepted in Experiments 1 to 3, material names accepted in Experiment 3, degree of orientation change in Experiments 1, 2, and 4, and counterbalancing sets for Experiments 1 to 4.

Object Names	Accepted Alternative Names	Accepted Material Names	Orientation Change	E1/2 Set	E3 Set	E4 Set
Alarm clock		Metal, glass	90	A	A	B
Bottle	Milk bottle/carton	Plastic	90	E	C	F
Bulldog clip	Clip	Metal	90	D	C	H
Calculator		Plastic, glass	90	B	B	B
Camera		Plastic, glass	90	A	A	A
Cassette	Tape	Plastic	90	E	C	C
Comb		Plastic	90	C	B	N/A
Fork		Metal	90	A	A	N/A
Hammer		Wood, metal	90	A	A	A
Holepunch		Plastic, metal	90	B	A	N/A
Kettle		Plastic	90	E	C	N/A
Key		Metal	90	B	A	B
Knife		Metal	90	D	C	N/A
Ladle		Metal	90	C	B	D
Measuring jug	Plastic jug, jug	Plastic	90	A	A	H
Mouse		Plastic	90	A	A	H

Mug	Cup	Pot, ceramic	90	D	C	N/A
Nail		Metal	90	C	B	E
Padlock	Lock, bike lock	Metal	90	C	B	G
Paintbrush	Pastry brush	Wood, fibres	90	C	B	N/A
Pen		Plastic, metal	90	B	A	C
Pencil		Wood	90	E	C	F
Screwdriver		Plastic, metal	90	D	B	E
Shoe		Leather	90	D	B	N/A
Spanner	Wrench	Metal	90	C	B	C
Spoon		Metal	90	B	A	N/A
Stapler		Metal	90	C	B	D
Tap		Metal	90	A	A	E
Toothbrush		Plastic, fibres	90	E	C	N/A
Tweezers		Metal	90	E	C	D
Whisk	Mixer	Metal	90	A	A	N/A
Whistle		Metal	90	C	B	G
Cigarette lighter		Plastic, metal	180	E	C	E
Corkscrew	Bottle opener	Wood, metal	180	B	B	B
Dustpan		Plastic	180	B	A	N/A
Funnel		Plastic	180	D	C	D
Glasses	Sunglasses	Plastic, glass	180	D	B	H
Peg		Plastic, metal	180	D	C	N/A
Plug		Plastic, metal	180	B	A	F
Razor		Plastic	180	A	A	A
Remote control	TV clicker	Plastic	180	C	B	G

Scissors		Metal	180	D	C	G
Sieve		Plastic	180	E	C	F
Tin opener	Can opener	Plastic, metal	180	E	C	A
Torch		Plastic, glass	180	B	B	C

APPENDIX II|

The 16 experimental sets of objects presented in Experiments 6 and 7, Chapter 4. Alternative acceptable names for each object are given in brackets.

Object name	Object set	Object name	Object set
Kettle	A	Comb	I
Paintbrush	A	Pliers	I
Spoon	A	Screwdriver	I
Cup (Mug)	B	Cheese grater	J
Hammer	B	Hairbrush (Brush)	J
Spanner (Wrench)	B	Tweezers	J
Alarm clock	C	Corkscrew	K
Razor	C	Dustpan	K
Tongs	C	Sieve	K
Battery	D	Funnel	L
Candle	D	Measuring jug	L
Pencil	D	Whistle	L
Bolt (Screw)	E	Light bulb	M
Fork	E	Scissors	M
Stapler	E	Whisk	M
Bulldog clip	F	Pen	N
Calculator	F	Toothpaste (Tube, glue)	N
Ladle	F	Torch (Flashlight)	N
Cassette tape	G	Electric plug	O
Remote control	G	Milk bottle with handle	O
Toothbrush	G	Tap	O

Clothes peg	H	Glasses (Sunglasses)	P
Padlock (Lock)	H	Holepunch	P
Wine glass	H	Teapot	P

APPENDIX III|

Results of visual rating by items of stimuli used in Chapter 5 (1=low typicality or similarity to standard, 7=high).

Object Name (alternative names)	Typicality Ratings			Similarity To Standard		Different Size Rated More Similar (%)
	Standard	Different Size	Different Shape	Different Size	Different Shape	
Battery	4.58	5.63	4.83	4.5	2.7	60
Bolt (Screw)	2.67	3.33	1.67	5.1	5.3	70
Book	6.08	5.71	5.46	5.8	5.3	90
Bulldog Clip	4.79	4.38	4.04	6.1	2.3	100
Can	6.42	4.79	4.08	4	4.6	50
Candle	5.13	4.75	4.75	3.7	1.5	70
Comb	5.13	5.75	4.92	4.8	5.2	40
Food Container (Box)	5.50	6.00	4.54	4	4.2	70
Funnel	5.58	5.58	3.08	5.1	4.2	100
Glass Bottle	5.50	4.75	4.46	4.3	3	90
Grater	4.17	3.13	5.21	4.8	3.7	70
Hammer	5.88	4.13	5.79	4	4.2	40
Holepunch	5.38	4.83	5.71	2.7	5.2	0
Key	5.38	4.38	4.17	4.6	4.9	80
Lid	4.71	5.17	4.92	5.2	4.8	80
Light Bulb	6.00	6.00	3.67	5.2	2.9	100
Measuring Jug	4.83	6.00	5.29	4.3	3.9	80

Milk Bottle	5.38	5.17	4.42	4	3.6	80
Mug (Cup)	5.83	5.29	5.00	4.6	3.7	90
Padlock (Lock)	4.21	5.79	4.33	4.1	2.5	100
Paintbrush	5.46	4.63	2.67	2.1	4.1	20
Pen	5.88	3.58	5.83	4.8	3.9	90
Plantpot	4.88	4.88	4.88	5.1	5.4	40
Ruler	5.96	5.63	4.71	5.9	5.5	60
Scissors	6.33	5.75	5.04	6.7	3.3	90
Screwdriver	5.29	5.08	5.46	5.4	4.6	80
Sieve	5.54	4.88	5.83	5.1	4.2	90
Spanner (Wrench)	5.88	4.71	4.75	5.3	4.4	100
Spoon	5.75	5.50	5.38	5.1	5	20
Stapler	5.75	2.50	5.88	2	4.1	0
Tape Measure	6.00	4.75	5.79	5.5	5.8	30
Tin	4.17	4.54	5.63	5.3	4.7	60
Toothbrush	4.88	5.33	6.04	4.8	3.8	70
Torch	5.38	5.54	4.33	5	4.8	70
Whisk	5.96	5.46	5.46	5.9	5.5	30
Wine Glass	5.29	4.29	5.75	3	2.7	60
Mean	5.32	4.93	4.83	4.7	4.2	66

APPENDIX IV|

Names and accepted alternative names of the new objects presented in Experiments 8 and 9, Chapter 5

Alarm clock	Dustpan	Jar	Pliers	Teapot
Calculator	Electric plug	Kettle	Razor	Tin opener
Camera	Fork	Knife	Salt cellar (salt shaker)	Toothpaste tube (glue)
Cassette tape	Glasses (sunglasses)	Ladle	Shoe (trainer)	Tweezers
Corkscrew	Hairbrush (brush)	Placemat	Tap	Whistle