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

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Abstract. Two experiments were carried out to examine the effects of dominant right versus non-dominant left exploration hand and left versus right object orientation on haptic recognition of familiar objects. In experiment 1, participants named 48 familiar objects in two blocks. There was no dominant-hand advantage to naming objects haptically and there was no interaction between exploration hand and object orientation. Furthermore, priming of naming was not reduced by changes of either object orientation or exploration hand. To test whether these results were attributable to a failure to encode object orientation and exploration hand, experiment 2 replicated experiment 1 except that the unexpected task in the second block was to decide whether either exploration hand or object orientation had changed relative to the initial naming block. Performance on both tasks was above chance, demonstrating that this information had been encoded into long-term haptic representations following the initial block of naming. Thus when identifying familiar objects, the haptic processing system can achieve object constancy efficiently across hand changes and object-orientation changes, although this information is often stored even when it is task-irrelevant.

1 Introduction

Understanding object constancy is central to our understanding of object recognition. Object constancy is our ability to recognise objects across a wide variety of conditions that disruptively transform perceptual inputs. For example, the retinal image of a car seen from above is quite different from the retinal image of the same car seen from behind, yet we can identify the car efficiently from both views. A significant body of research has examined how the visual object recognition system generalises over such variation. We are also capable of recognising objects both quickly and accurately using our haptic, active touch sense (Klatzky et al 1985; Lederman and Klatzky 1990). Excellent cross-modal priming (Reales and Ballesteros 1999) suggests that there are substantial representational similarities between the two modalities, and the relationship between visually and haptically derived representations has come under scrutiny. One consequence of this interest in comparing visual to haptic object recognition is that recent research has begun to investigate the achievement of haptic object constancy.

Haptic object recognition has been shown to exhibit orientation dependence similar to that observed in visual object recognition (Craddock and Lawson 2008; Lacey et al 2007; Lawson in press; Newell et al 2001). Changes of orientation constitute a disruptive transformation in perceptual input for both modalities. 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 with a more ecologically valid set of familiar objects. In this study we investigated 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).

2 The influence of right-handed 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 lateralisation. 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 and Brismar 1999). Generally, the left hemisphere is more specialised for language understanding and production, whereas the right hemisphere is more specialised for spatial processing (Corballis 2003; Gazzaniga 2000). The literature on lateralisation of hand function has been mixed (Millar and Al-Attar 2003; Summers and Lederman 1990). For example, some researchers have shown left-hand advantages for naming Braille letters (Hermelin and 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 et al 1982; Millar 1984, 1987; Wells-Jensen et al 2008). Heller et al (1990) found an advantage for left-hand processing of numbers represented with a vibrotactile display. Heller et al (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 et al (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 how such hemispheric differences might influence haptic recognition of more complex, 3-D stimuli has been relatively neglected. Some studies reported a left-hand advantage when recognising wire shapes (B Milner and Taylor 1972; Riege et al 1980). However, many of the studies on haptic object recognition do not mention or control for handedness (eg Ballesteros et al 1999; Easton et al 1997; Klatzky et al 1985, 1987; Lacey and Campbell 2006; Lacey et al 2007; Lederman and Klatzky 1987; Reales and Ballesteros 1999), or permitted bimanual exploration (Craddock and Lawson 2008, 2009, submitted; 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 (eg Amedi et al 2001; Cooke et al 2007; Lawson in press; Miquée et al 2008). There was a range of good methodological reasons why the researchers 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-hand performance and left-hand performance on tasks involving 3-D objects.

The findings of the few studies that have compared performance between hands have been mixed. Summers and Lederman (1990) found no evidence for lateralisation 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 et al 1993a, 1993b, 1994). Fagot et al (1993a) 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 hand, irrespective of the hand with which it was initially explored. Fagot et al (1993b) 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 with 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 and Klatzky 1987, 1990), whereas Summers and Lederman (1990) found no overall effect of handedness on haptic object recognition. 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 to differences only in exploratory hand movements.

Some researchers have 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 et al (2005) found that discrimination of sequentially explored sinusoidal gratings was better with the same hand than discrimination with 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 generalise to the recognition of more complex, familiar objects. We investigated this issue in the two experiments presented here. We hypothesised 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 the 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 to his or her 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 as a result of the left-hemisphere specialisation 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 lateralisation 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 account 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 3 s.

In section 3 we review evidence 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.

3 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 (eg Biederman and Gerhardstein 1993; Hayward 2003; Tarr and Bülthoff 1995; Tarr and Cheng 2003). Rotations in plane or depth can influence both naming and priming of naming in vision (Jolicoeur 1985, 1990; Lawson 1999; Lawson and Jolicoeur 2003). 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 and Cooper 1991; Cooper et al 1992; Srinivas 1996; Srinivas et al 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 for depth-rotated pictures of novel objects.

Far less research has been devoted to investigating the orientation sensitivity of haptic than of visual object recognition. Craddock and Lawson (2008) 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 and Humphreys 2005; Lacey et al 2007; Lawson, in press; Newell et al 2001). As noted earlier, Newell et al (2001) suggested that orientation dependence arises in haptics because, owing 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.

In several studies the effects of mirror reflection on performance of haptic and tactile mental rotation tasks have been examined. Performance has generally been found to be similar to that observed in vision (see Prather and Sathian 2002 for a review). Only in one study to date have the effects of mirror-image reflection on haptic object recognition been examined. Srinivas et al (1997) found that haptic and visual recognition and memory of novel 2-D 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 2-D 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 2-D patterns. In contrast, they argued that right – left orientation is not informative for identifying most familiar 3-D objects—a mirror-image reflection of a car is still a car—and thus that their findings may not generalise to visual and haptic recognition of 3-D 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 by 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 et al 1991; James et al 2003; A D Milner and Goodale 2008; Rice et al 2007; Valyear et al 2006). For example, Humphreys and Riddoch (2001) described a patient who could not select a visually presented object when given its name (eg “pick up the cup”) or a perceptual description (eg “pick up the red object”), but who could choose the correct object when told of an action associated with that object (eg “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 and 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 (eg Chao and Martin 2000; Creem-Regehr and Lee 2005; Grèzes and Decety 2002; Grèzes et al 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 and Ellis 1998, 2004).

Others have examined the reverse interaction: whether motor representations of object-directed actions influence visual object recognition. Bub et al (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 et al

(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 (eg dustpan then frying pan, both of which are grasped by the handle), suggesting that priming an action representation can facilitate object recognition. Similarly, Vainio et al (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 generalise to recognition over longer time periods.

These studies provide some evidence that actions and motor representations can affect object recognition, but the stimuli have only been presented 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 artifacts, 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.

We conducted two experiments 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 because of hemispheric lateralisation. In addition, the results of one-handed exploration in experiments 1 and 2 here can also be compared to those of two-handed exploration in Craddock and Lawson (2008) 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 for acting 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 identifying 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-hand 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 Experiment 1

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 hand or the left hand, and both exploration hand and object orientation could change between blocks.

4.1 *Method*

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

4.1.2 *Stimuli.* 48 familiar objects were used—see the appendix (table A1, a supplementary figure showing all 48 objects in their right orientations is available online, see http://dx.doi.org/10.1068/p6312). Objects were typical examples of man-made, nameable, familiar artifacts from a wide range of categories. They had a diversity of shapes, sizes, textures, and functions. Each object was glued to a 20 cm × 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 on the basis of 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 1). Some objects had minor deviations from perfect bilateral symmetry about the vertical plane (eg hammer, scissors, and tongs), but performance on these items was consistent with that on other items.

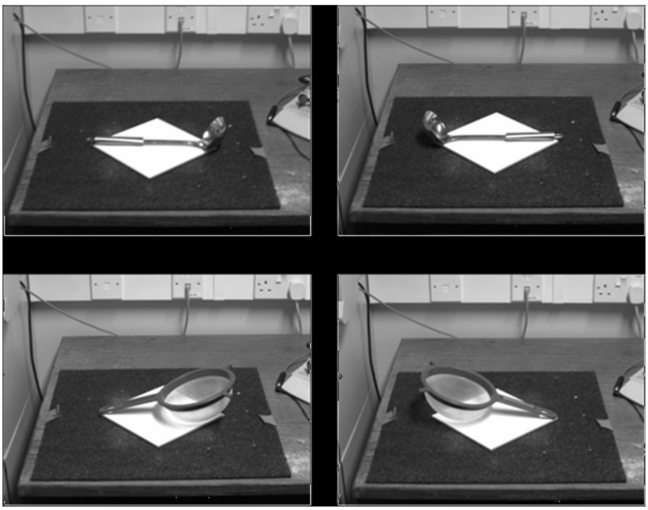

Figure 1. Ladle and sieve used in experiments 1 and 2, shown in their respective left (on the left) and right (on the right) orientations.

4.1.3 *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 1). The tape allowed participants to locate the starting hand positions consistently without vision. The 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 twenty-four trials: one block of left-hand trials, and one block of right-hand trials.

The order of presentation of left-hand (L) and right-hand (R) sub-blocks was counterbalanced across the prime and target blocks with four orders: LR – LR, LR – RL, RL – LR, and RL – RL. Before each sub-block, the experimenter instructed participants to use either the right hand or the 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 for the set allocation). In the prime block, eight of these sets were presented in left object orientations and eight in right object orientations. In the 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 (eg 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 with a Latin Square design across all the groups such that no two groups received the objects in the same condition (eg 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 (Cohen et al 1993) generated the order of presentation of objects within each block and was used to record responses. The order of right-hand and left-hand trials was fixed according to the counterbalancing scheme described above; order of presentation of objects within those blocks was randomised.

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 his or her exploration hand on the appropriate tape marker. A single, low-pitched warning beep was played, followed by a high-pitched double beep 1 s 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 (RTs) were recorded from the offset of the double beep with a microphone headset attached to a Macintosh computer as a voice key.[1] 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 his or her response (such as saying "erm") or the voice key was not activated by the response (voice key errors); and trials on which the participants either started to move too early or used the wrong hand (movement errors).

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

4.2 *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-handed versus two-handed haptic object recognition using data from Craddock and Lawson (2008). 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, RTs and errors were pooled for each participant across the objects that he or she 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. Throughout this article, F-values in the by-participants and by-items analyses are reported as 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.

4.2.1 *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 ($F^{\mathrm{p}}_{1,16} = 0.005$, $p = 0.9$; $F^{\mathrm{i}}_{1,32} = 0.150$, $p = 0.7$) or errors ($F^{\mathrm{p}}_{1,16} = 0.010$, $p = 0.9$; $F^{\mathrm{i}}_{1,32} = 0.006$, $p = 0.8$). 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 (4325 ms; 12% errors) and the left hand (4215 ms, 12% errors).

There was also no effect of object orientation on RTs ($F^{\mathrm{p}}_{1,16} = 0.389$, $p = 0.5$; $F^{\mathrm{i}}_{1,32} = 1.694$, $p = 0.2$) or errors ($F^{\mathrm{p}}_{1,16} = 0.061$, $p = 0.8$; $F^{\mathrm{i}}_{1,32} = 0.036$, $p = 0.9$). There was no evidence for an advantage for right-oriented objects (4349 ms; 12% errors) over left-oriented objects (4293 ms; 12% errors).

Finally, there was no interaction between exploration hand and object orientation for RTs ($F^{\mathrm{p}}_{1,16} = 0.418$, $p = 0.5$; $F^{\mathrm{i}}_{1,32} = 0.107$, $p = 0.7$) or errors ($F^{\mathrm{p}}_{1,16} = 1.209$, $p = 0.3$; $F^{\mathrm{i}}_{1,32} = 0.670$, $p = 0.4$). Mean RTs and errors were similar (around 4300 ms; 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.

4.2.2 *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 ($F^{\mathrm{p}}_{1,16} = 4.615$, $p = 0.05$; $F^{\mathrm{i}}_{1,32} = 3.985$, $p = 0.05$) but not on errors ($F^{\mathrm{p}}_{1,16} = 1.003$, $p = 0.3$; $F^{\mathrm{i}}_{1,32} = 0.800$, $p = 0.4$). 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 150 ms faster, though no more accurately, with their left hand (3115 ms; 6% errors) than with their right hand (3267 ms; 7% errors).

There was no effect of target block object orientation on RTs ($F^{\mathrm{p}}_{1,16} = 1.928$, $p = 0.2$; $F^{\mathrm{i}}_{1,32} = 2.833$, $p = 0.1$) or errors ($F^{\mathrm{p}}_{1,16} = 0.016$, $p = 0.9$; $F^{\mathrm{i}}_{1,32} = 0.008$, $p = 0.9$). There was no evidence for an advantage for right-oriented objects (3143 ms; 7% errors) over left-oriented objects (3240 ms; 7% errors).

There was only a marginally significant interaction between exploration hand and object orientation for RTs ($F^{\mathrm{p}}_{1,16} = 4.467$, $p = 0.05$; $F^{\mathrm{i}}_{1,32} = 1.383$, $p = 0.2$) and no significant interaction for errors ($F^{\mathrm{p}}_{1,16} = 2.494$, $p = 0.1$; $F^{\mathrm{i}}_{1,32} = 1.883$, $p = 0.2$). Tukey's HSD tests ($\alpha = 0.05$) revealed that naming left-oriented objects with the right hand was slower (3370 ms; 8% errors) than naming either left-oriented (3109 ms; 7% errors) or right-oriented objects (3121 ms; 5% errors) with the left hand, but no faster than naming right-oriented objects with the right hand (3164 ms; 8% errors). 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.

4.2.3 *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 with both prime and target block exploration hand (left or right) and object orientation (left or right) would produce sixteen 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 with 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 ($F^{\mathrm{p}}_{1,16} = 0.258$, $p = 0.6$; $F^{\mathrm{i}}_{1,32} = 0.009$, $p = 0.9$) or errors ($F^{\mathrm{p}}_{1,16} = 1.260$, $p = 0.3$; $F^{\mathrm{i}}_{1,32} = 0.698$, $p = 0.4$). Although there was substantial priming, with naming being over 1 s faster in the target block, there was no benefit to using the same hand in both blocks (1231 ms faster RTs; 6% decrease in errors) compared to using a different hand in each block (1183 ms, 5% decrease in errors).

There was also no significant effect of object orientation on RTs ($F^{\mathrm{p}}_{1,16} = 0.000$, $p = 0.9$; $F^{\mathrm{i}}_{1,32} = 0.071$, $p = 0.8$) or errors ($F^{\mathrm{p}}_{1,16} = 0.002$, $p = 0.9$; $F^{\mathrm{i}}_{1,32} = 0.006$, $p = 0.9$). Naming of objects placed in the same orientation in both blocks was neither faster nor more accurate (1206 ms faster RTs; 5% decrease in errors) than naming of objects placed in different orientations in each block (1208 ms; 5% decrease in errors).

Finally, there was no interaction between exploration hand and orientation for either the priming of RTs ($F^{\mathrm{p}}_{1,16} = 1.128$, $p = 0.3$, see figure 2a; $F^{\mathrm{i}}_{1,32} = 0.012$, $p = 0.9$) or of errors ($F^{\mathrm{p}}_{1,16} = 1.145$, $p = 0.3$, see figure 2b; $F^{\mathrm{i}}_{1,32} = 0.382$, $p = 0.5$).

4.2.4 *One-handed versus two-handed object naming.* 24 of the objects presented in experiment 1 here were also presented (and placed in the same orientation) in experiment 1 of Craddock and Lawson (2008). In the latter experiment, the same procedure was used as in experiment 1 here, except that the participants used both hands to recognise the objects. 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: $t_{60} = 1.672$, $p = 0.1$; errors: $t_{60} = 2.846$, $p = 0.006$) and,

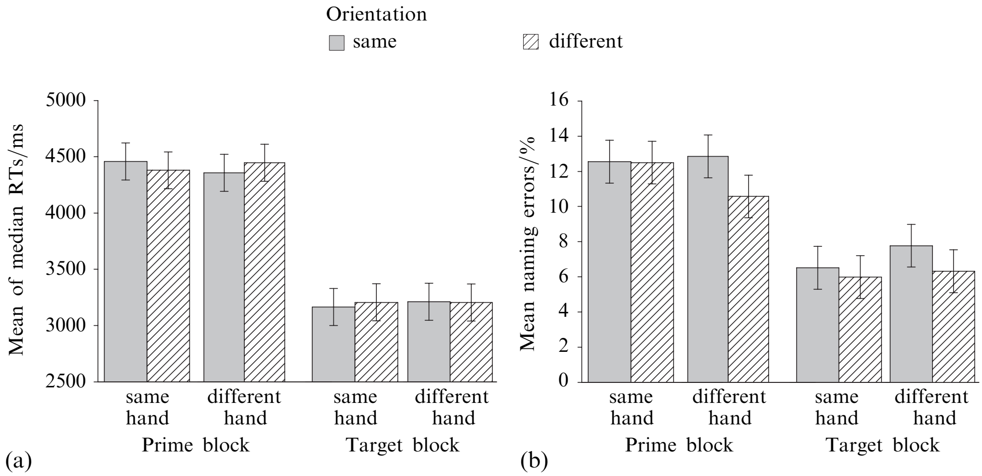

Figure 2. Means for (a) median naming RTs and (b) percentage naming errors in prime and target blocks separated by exploration hand and object orientation. Error bars show 95% within-participants confidence intervals (Loftus and Masson 1994). Note that 'hand' and 'orientation' were dummy variables in the prime block.

marginally, by items ($t_{23} = 1.457$, $p = 0.08$; $t_{23} = 1.662$, $p = 0.06$). Naming was marginally slower and significantly less accurate when using one hand (4180 ms; 9% errors) than when using both hands (3766 ms; 3% errors). Similarly, in the target block, although there was no effect of the number of exploration hands by participants ($t_{60} = 1.054$, $p = 0.3$; errors $t_{60} = 0.972$, $p = 0.3$), there was a significant effect by items on RTs ($t_{23} = 1.822$, $p = 0.04$) and, marginally, on errors ($t_{23} = 1.488$, $p = 0.08$). Again, naming tended to be slower and less accurate when one hand was used (3165 ms; 5% errors) than when both hands were used (2978 ms; 4% errors).

4.3 *Discussion*

First, although all participants in experiment 1 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. Contrary to the present results, Craddock and Lawson (2008) reported that 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 tested by Craddock and Lawson (2008). 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 1. 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 1 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 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 and 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 and Campbell 2006). The lack of an effect of orientation changes on priming of naming replicates experiment 1 of Craddock and 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 an earlier study that we reported in Craddock and Lawson (2008) that tested the same objects, there was evidence for superior haptic recognition when two hands were used. For example, initial naming with two hands was 414 ms 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 et al 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 Craddock and Lawson (2008), 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 3-D, 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 (eg Lederman et al 1990; Loomis et al 1991).

5 Experiment 2

One explanation for the absence of effects on priming in experiment 1 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 (Craddock and Lawson 2008). In their 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 1 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 1 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 Craddock and Lawson (2008), we found that participants were quite accurate at explicitly detecting whether an object had changed orientation between study and test. However, in experiment 1 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 (eg Lawson 2004; Seamon and Delgado 1999), and thus explicitly remembering object orientation here may be harder than in Craddock and Lawson (2008). To test this hypothesis we replicated experiment 1 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.

5.1 *Method*

5.1.1 *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 years. 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.

5.1.2 *Stimuli, design, and procedure.* The same set of 48 objects as used in experiment 1 was used in experiment 2. The procedure was similar to that of experiment 1, 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.

5.2 *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; $t_{15} = -8.085$, $p < 0.001$) and object orientation (23% errors; $t_{15} = -8.998$, $p < 0.001$). 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 ($t_{30} = 2.878$, $p = 0.004$). In experiment 2 of Craddock and Lawson (2008), 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.

5.2.1 *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 ($F^{\mathrm{p}}_{1,15} = 14.315$, $p = 0.002$; $F^{\mathrm{i}}_{1,32} = 6.379$, $p = 0.017$) and for errors ($F^{\mathrm{p}}_{1,15} = 7.614$, $p = 0.015$; $F^{\mathrm{i}}_{1,32} = 33.986$, $p < 0.001$). Participants were faster and more accurate when the object was in the same orientation (3549 ms; 16% errors) than in a different orientation (3941 ms; 26% errors). There was a main effect of exploration hand for RTs ($F^{\mathrm{p}}_{1,15} = 5.068$, $p = 0.04$; $F^{\mathrm{i}}_{1,32} = 8.250$, $p = 0.007$) but not for errors ($F^{\mathrm{p}}_{1,15} = 1.802$, $p = 0.2$; $F^{\mathrm{i}}_{1,32} = 0.003$, $p > 0.9$). Participants were faster but no more accurate at remembering the original object orientation when the object was explored with the same hand (3627 ms; 22% errors) than when the exploration hand switched between blocks (3863 ms; 20% errors). There was no interaction between object orientation and exploration hand for RTs ($F^{\mathrm{p}}_{1,15} = 1.726$, $p = 0.2$; $F^{\mathrm{i}}_{1,32} = 0.158$, $p = 0.7$) or for errors ($F^{\mathrm{p}}_{1,32} = 1.146$, $p = 0.3$; $F^{\mathrm{i}}_{1,32} = 2.608$, $p = 0.1$) (see figure 3).

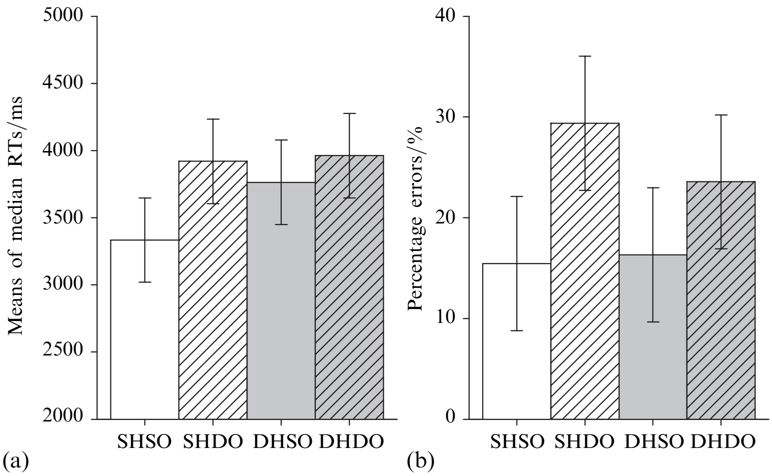

Figure 3. (a) Means of median RTs and (b) mean percentage errors for the object-orientation group in experiment 2. Bars depict data from same-hand, same-orientation (SHSO); same-hand, different-orientation (SHDO); different-hand, same-orientation (DHSO); and different-hand, different orientation (DHDO) 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 and Masson 1994).

5.2.2 *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 ($F^{\mathrm{p}}_{1,15} = 2.187$, $p < 0.2$; $F^{\mathrm{i}}_{1,32} = 2.168$, $p < 0.2$) or errors ($F^{\mathrm{p}}_{1,15} = 0.682$, $p > 0.4$; $F^{\mathrm{i}}_{1,32} = 1.195$, $p < 0.3$). Performance when remembering the original exploration hand was similar if the object was in the same orientation (4396 ms; 30% errors) or a different orientation (4626 ms; 34% errors). There was also no effect of exploration hand on RTs ($F^{\mathrm{p}}_{1,15} = 0.119$, $p > 0.7$; $F^{\mathrm{i}}_{1,32} = 0.098$, $p > 0.7$) or errors ($F^{\mathrm{p}}_{1,15} = 0.081$, $p > 0.7$; $F^{\mathrm{i}}_{1,32} = 0.624$, $p > 0.4$). Performance was similar whether the object was explored with the same hand (4483 ms; 31% errors) or the other hand (4538 ms; 33% errors). The interaction of object orientation with exploration hand for RTs was not significant by participants ($F^{\mathrm{p}}_{1,15} = 2.131$, $p < 0.2$) but it was by items ($F^{\mathrm{i}}_{1,32} = 5.247$, $p < 0.03$) and for errors ($F^{\mathrm{p}}_{1,15} = 38.550$, $p < 0.001$; $F^{\mathrm{i}}_{1,32} = 44.882$, $p < 0.001$) (see figure 4). A posteriori Tukey's HSD comparisons with $\alpha = 0.05$ revealed that participants were similarly accurate when both exploration hand and object orientation were the same (SHSO: 4234 ms; 18% errors) as when both were different (DHDO: 4519 ms; 23% errors). In contrast, they were less accurate if object orientation but not exploration hand changed (SHDO: 4733 ms; 45% errors) or if the exploration hand but not object orientation changed (DHSO: 4558 ms; 42% errors).

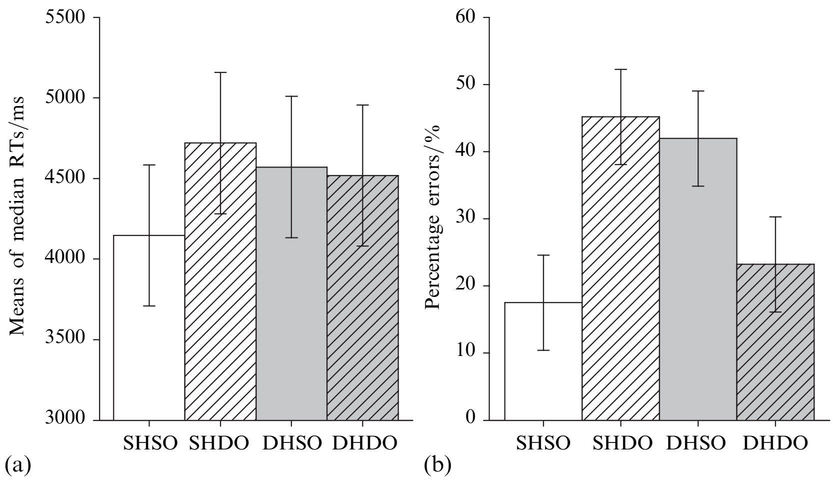

Figure 4. (a) Means of median RTs and (b) mean percentage errors for the exploration hand group in experiment 2. Bars depict data from same-hand, same-orientation (SHSO); same-hand, different-orientation (SHDO); different-hand, same-orientation (DHSO); and different-hand, different-orientation (DHDO) 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 and Masson 1994).

5.2.3 *Effects of exploration hand and object orientation on initial naming.* Although the naming block was not the critical block in experiment 2, we analysed its data for comparison to experiment 1. The naming block was identical for both groups, so their data was combined. This naming block was also identical to that of experiment 1 except that left-hand and right-hand trials were blocked in experiment 1 but were interleaved in experiment 2. 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 ($F^{\mathrm{p}}_{1,30} = 0.407$, $p = 0.5$; $F^{\mathrm{i}}_{1,32} = 0.043$, $p = 0.8$) or errors ($F^{\mathrm{p}}_{1,30} = 1.662$, $p = 0.2$; $F^{\mathrm{i}}_{1,32} = 2.917$, $p = 0.1$). Participants were neither faster nor more accurate with the right hand (4513 ms; 8% errors) than with the left hand (4414 ms; 10% errors). There was no effect of object orientation on RTs ($F^{\mathrm{p}}_{1,30} = 1.030$, $p = 0.3$; $F^{\mathrm{i}}_{1,32} = 0.624$, $p = 0.4$) or errors ($F^{\mathrm{p}}_{1,30} = 0.094$, $p = 0.8$; $F^{\mathrm{i}}_{1,32} = 0.119$, $p = 0.7$).

Participants were neither faster nor more accurate if the object was in a right orientation (4562 ms; 8% errors) than if it was in a left orientation (4365 ms; 9% errors). There was no interaction between exploration hand and object orientation for RTs by participants ($F^{p}_{1,30} = 2.038$, $p = 0.2$), but there was by items ($F^{i}_{1,32} = 19.298$, $p < 0.001$). There was no significant interaction for errors ($F^{p}_{1,30} = 0.001$, $p > 0.9$; $F^{i}_{1,32} = 0.004$, $p > 0.9$). The significant interaction for RTs by items was neither in the expected direction nor consistent with experiment 1, so will not be discussed further. However, the means are reported here for completeness (left hand, left orientation: 4685 ms; 10% errors; left hand, right orientation: 4340 ms; 9% errors; right hand, left orientation: 4250 ms; 7% errors; right hand, right orientation: 4827 ms; 7% errors).

5.3 *Discussion*

The main finding from experiment 2 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 with those from the name priming task used in experiment 1 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. Participants 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 3-D objects. In experiment 2, 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 encoded only 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.

6 General discussion

Neither exploration hand nor object orientation affected initial naming in either experiment 1 or in experiment 2, 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 1. However, both initial exploration hand and initial object orientation were encoded, since participants were able to recall these factors in an unexpected task in experiment 2. 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 (eg Nalçaci et al 2001; Triggs et al 2000). As noted earlier, previous observations of right-hand versus left-hand advantages have provided mixed evidence that is often highly task-specific (Millar and Al-Attar 2003; Summers and 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, respectively, are specialised, 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 1, priming of naming of haptically explored familiar objects was unaffected by changes of exploration hand or changes of object orientation, replicating and extending Craddock and 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. In experiment 2 we 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 1 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 and Brandt 2003; Buchner and Wippich 2000; Meier and 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 (Craddock and Lawson 2008, 2009), and that orientation sensitivity emerges even for familiar objects (Lawson, in press). 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 generalising across orientation changes (eg Craddock and Lawson 2008; Lacey et al 2007; Newell et al 2001) and size changes (Craddock and Lawson, 2009, submitted). 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, 2002, 2005) and with behavioural evidence of efficient crossmodal transfer in object processing (Lawson, 2009; Reales and Ballesteros 1999). We have shown here that haptic recognition of familiar objects generalises 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.

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Appendix: Table A1. The sixteen experimental sets of objects presented in experiments 1 and 2. Alternative acceptable names for each object are given in parentheses.

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

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