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An Investigation into the Cause of Orientation-Sensitivity in Haptic Object Recognition *

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Abstract

Object orientation influences visual and haptic recognition differently. This could be caused by the two modalities accessing different object representations or it could be due to differences in how each modality acquires information. These two alternatives were investigated using sequential haptic matching tasks. Matches presented the same object twice. Mismatches presented two similarly-shaped objects. Objects were either both placed at the same orientation or were rotated 90° in depth from each other. Experiment 1 manipulated exploration time to test if longer durations weakened orientation-sensitivity by allowing orientation-invariant representations to be extracted. This hypothesis was not supported. Experiment 2 investigated whether the same-orientation advantage resulted from general spatial or motor action cueing rather than the involvement of orientation-specific object representations. To distinguish between these two possibilities, people did a secondary task interleaved within the matching task. They reported the orientation of a fork or spoon which was presented in between the first and second objects. The main axis of the fork/spoon was the same as that of the final object, equating spatial and motor cueing across the same-orientation and orientation-change conditions. Nevertheless, matching remained orientation-sensitive. Together these results suggest that there are separate visual and haptic stored, orientation-specific perceptual representations of objects.

Keywords

Haptic, object recognition, orientation, modality, matching, representations, visual

1. Introduction

A primary goal for both vision and haptics is the representation of the 3D shape of objects. This observation has encouraged research investigating whether these two

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modalities share processes and representations. This could be more efficient than each sense processing shape independently. It should also benefit crossmodal processing (trying to recognise an object by touch after having seen it, and *vice versa*) and, probably more importantly, multisensory processing (Takahashi *et al.*, 2009). However, fundamental differences in information acquisition for vision *versus* haptics and in the reference frames used by the two modalities may make it difficult for them to use common processes and representations (Volcic *et al.*, 2010). This issue has been investigated from a variety of perspectives, for example, using imaging (e.g., Amedi *et al.*, 2005; Lacey *et al.*, 2009), multidimensional scaling of similarity ratings (Cooke *et al.*, 2007; Gaissert *et al.*, 2010) and psychophysical experiments (e.g., Craddock and Lawson, 2009; Lawson, 2009; Newell *et al.*, 2001). The latter approach is that taken here. If visual and haptic inputs both access the same, stored object representations then factors influencing the use of these shared representations should influence visual and haptic object recognition in similar ways. There is good evidence that visual object representations encode orientation, as reviewed below. The present studies, therefore, examined whether object orientation is coded in the stored representations used in haptic recognition.

The effect of the orientation of an object on its recognition has been of long-standing interest to psychologists due to its central but disputed role in theoretical models of visual object representation. Some theories predict that object recognition should be largely orientation insensitive (e.g., Biederman, 1987; Hummel and Biederman, 1992; Marr, 1982; Marr and Nishihara, 1978) whereas others predict it to be largely orientation sensitive (e.g., Bülthoff and Edelman, 1992; Tarr and Pinker, 1990; Ullman, 1998). Numerous studies have, therefore, investigated the circumstances under which visual object recognition is orientation-sensitive.

Object orientation has at least a superficially similar effect on recognition across the two modalities. It is now well-established that visual and haptic object recognition are both usually harder if the to-be-identified object is presented at a different orientation compared to when it was initially recognised. This orientation-sensitivity is found for both short-term sequential matching tasks and for long-term recognition memory tasks for both vision (e.g., Hayward, 1998; Hayward and Williams, 2000; Lawson, 2004, 2009; Lawson and Bülthoff, 2006; Lawson and Humphreys, 1996, 1998, 1999; Lawson *et al.*, 1994, 2003; Srinivas, 1995; Thoma and Davidoff, 2006; Vuilleumier *et al.*, 2002) and for haptics (e.g., Craddock and Lawson, 2008; Ernst *et al.*, 2007; Forti and Humphreys, 2005; Lacey *et al.*, 2007; Lawson, 2009; Newell *et al.*, 2001).

2. Experimental

The basic finding of broadly similar costs of changes to object orientation for vision and haptics needs to be examined more carefully before it can be taken as strong evidence that both modalities are accessing the same, orientation-specific perceptual representations. Haptics and vision share the goal of representing 3D object shape.

It is, therefore, to be expected that a factor which profoundly affects the sensory input for this task, such as object orientation, influences recognition in both modalities. In particular, this might occur even if two separate systems were involved in visual and haptic object recognition.

A stronger test of the similarity of the two modalities is to investigate the effects of orientation in combination with other factors. This approach was taken in Lawson (2009). Here, a series of sequential matching studies tested within-modal (visual then visual, VV, and haptic then haptic, HH) and cross-modal (visual then haptic, VH, and haptic then visual, HV) recognition. These experiments investigated whether a second factor, the difficulty of shape discrimination, modulated haptic and visual orientation-sensitivity. Discrimination difficulty was increased by presenting more similarly shaped objects on mismatch trials (e.g., easy: bed then lizard; medium: bed then chair; hard: bed then bed-chair morph). For VV matching, orientation-sensitivity was greater when discriminability was harder, replicating earlier research with 2D images of 3D objects (Lawson, 2004; Lawson and Bülthoff, 2008; Vuong *et al.*, 2009). In contrast, although HH and VH matching were both orientation-sensitive, the cost of coping with orientation changes was not modulated by discrimination difficulty. Instead, the two factors had additive effects. Finally, HV matching was orientation-invariant. These results provide evidence against the hypothesis that common, orientation-sensitive perceptual representations are accessed in both visual and haptic object recognition. Instead they suggest that the cause of orientation-sensitivity differs for visual *versus* haptic object recognition.

Similarly, Phillips *et al.* (2009) tested HH, VV and HV simultaneous matching of novel 3D objects. They manipulated (but did not directly report on) discrimination difficulty and they also varied stimulus complexity. They found relatively good cross-modal matching indicating that information can be shared efficiently across the two modalities. They further claimed that stimulus complexity had different effects on vision and touch. However, their stimuli were not presented to the two modalities in equivalent ways. Their haptic stimuli were real, 3D objects that could be freely explored and moved so for HH matching people could align the orientation of the two, simultaneously presented objects to aid their comparison. In contrast, their visual stimuli were continuously moving, computer-generated images on a computer screen which depicted 3D objects rotating about an arbitrary axis. For VV matching, the two objects were rotated about different axes and at different speeds and people had no control over either factor, so this task was very different to the HH matching task. Crucially, only in the former case could people compare objects at a fixed, static orientation specified by the participant. The VV matching task may thus have been harder than the HH task and this, in turn, might explain why stimulus complexity seemed to influence haptics more than vision.

These two studies illustrate the difficulty in making direct comparisons of visual and haptic object recognition. The speed and accuracy of shape perception and the nature of stimulus exploration by the two modalities usually differ substantially. It is, therefore, hard to determine whether these extraneous factors are the cause of any differences in object recognition across vision and haptics. However, careful experimentation allows us to tease apart the influence of fundamental differences between the modalities in information acquisition from effects due to the access and use of stored object representations. This was done in the present studies. These examined, first, whether the relatively long time course of haptic exploration modulates orientation-sensitivity and, second, whether the spatial location of the hand during exploration of one object can act as a generic cue to orientation which aids recognition of a subsequent object, for example on same-orientation trials in a matching task.

First, exploration duration was much greater haptically than visually in both Phillips *et al.* (2009) and Lawson (2009). As a result, the difference in the effect of discriminability on orientation-sensitivity for VV compared to HH matching reported by Lawson (2009) might result from differences in the encoding of visual and haptic information rather than indicating that different stored representations are used by the two modalities. Objects could be identified visually from a single viewpoint, with no need to use a sequence of eye movements to fixate different locations around the object. Furthermore, people could not see the far side of an object regardless of exploration duration, since they could make only limited movements of their head and body. This restricted information extraction to the front of an object due to self-occlusion (Lawson and Bracken, 2011). In contrast, people usually took several seconds to haptically explore objects, so detailed haptic representations were built up sequentially as they felt around the different parts of the object. The objects were small so the hand could access most parts of the object and people could quickly enclose most of the object in a single grasp, allowing gross shape to be extracted in parallel. However, the fine spatial information required to distinguish between similarly shaped objects was usually acquired by using just one or two fingers to explore the most important parts and this resulted in relatively slow, serial information acquisition (Lawson and Bracken, 2011; Lederman and Klatzky, 1990). Furthermore, there was no restriction on where people felt the object (except for the base) so, given sufficient exploration time, they could build up a full shape representation. In particular, in Lawson (2009) though the first object was always presented for 5 s for both VV and HH matching the second object was presented until a response was made. This exploration time varied. The easy discrimination HH group spent around 2 s exploring the second object whereas the hard discrimination HH group took about twice as long. This might have reduced orientation-sensitivity for the hard compared to the easy HH group because the hard group had more time to exhaustively explore all sides of the second object and so to build up more orientation-invariant (or multiple orientation-specific) object representations before responding. Based on the results for the VV task, the hard HH group had been expected to show greater orientation-sensitivity than the easy HH group as they did a more difficult shape discrimination task. However, the longer exploration duration for the hard HH group could have resulted in a masking of this predicted increase in orientation-sensitivity. This hypothesis was tested in Experiment 1 by restricting the exploration duration for the second object in a hard HH matching task to 2 s. If exploration time plays an important role in modulating orientation-sensitivity then this manipulation should increase orientation-sensitivity.

Second, haptic orientation-sensitivity in matching tasks could be due to general, spatial cueing or short-lived motor priming effects rather than being caused by orientation-sensitive, perceptual representations of objects. Priming and cueing effects are known to influence visually guided actions towards objects (e.g., Haffenden and Goodale, 2002; Hesse *et al.*, 2008; Jax and Buxbaum, 2010; Jax and Rosenbaum, 2007, 2009; Kroliczak *et al.*, 2008). When people reach for an object that they cannot see, they are likely to show similar spatial priming by returning their hand to where they last felt an object. Such priming would aid same-orientation HH matching. Here, the second, primed object would be in the same position as the first, priming object. This should make it easier to find and to locate the most important parts of the second object. In contrast, on orientation-change trials the hand might take longer to locate the second object in space and/or the fingers might initially touch uninformative areas. A further reason for the orientation-sensitivity of HH matching may be that objects are coded with respect to a main axis, for example the primary axis of elongation (see Craddock and Lawson, 2008). People would be quicker to locate this axis on same-orientation trials if their default assumption was that it had the same position as the main axis of the first object. For vision, any analogous priming effects for locating an object in space, finding its most informative parts and assigning object axes are likely to be much smaller because visual information is typically acquired fast and in parallel (Loomis *et al.*, 1991). This hypothesis was tested in Experiment 2 by warning people about the location and orientation of the to-be-matched object. If the HH matching benefit for same-orientation trials was due to general spatial or motor priming then such cueing should eliminate it. In contrast, if the same-orientation advantage was caused by object-specific priming of stored object representations then it should not be reduced by this cueing manipulation.

2.1. Experiment 1

Experiment 1 tested whether haptic orientation-sensitivity is modulated by exploration duration or shape discriminability using the same sequential HH matching task and stimuli as Lawson (2009). People did a hard shape discrimination task but, unlike Lawson (2009), they were instructed to stop exploring the second, to-be-matched object after just 2 s. This allowed two critical predictions to be tested. First, if haptic orientation-sensitivity is influenced by exploration duration, then reducing this duration to 2 s should increase orientation-sensitivity compared to the hard HH group tested by Lawson (2009). This group had unlimited exploration time and spent an average of 4 s exploring the second, to-be-matched object. For this comparison, shape discriminability was equally hard for both groups but exploration duration differed. Second, if haptic orientation-sensitivity is modulated by shape discriminability then orientation-sensitivity in the HH matching task for the hard, 2 s exploration group tested here should be greater than for the easy, unlimited exploration group tested by Lawson (2009). Here, exploration duration for the second, to-be-matched object was similar for both groups, at around 2 s, but shape discriminability differed.

2.1.1. Participants

There were 16 participants aged 19–28, all but one of whom were right-handed. Participants were undergraduate students from the University of Liverpool, U.K., who took part in the study for course credit.

2.1.2. Materials and Apparatus

The stimuli were 3D models of objects which were printed using a Dimension 3D ABS-plastic printer. Twenty sets of three white plastic morphs were produced. Each set comprised a startpoint morph, a midpoint morph, and an endpoint morph giving 60 stimuli in total (see Fig. 1). The preferred names for the startpoint and endpoint morphs were different basic level category labels, e.g., dog and pig. These were the same haptic stimuli used in Lawson (2009). Each morph was glued upright onto a 10 cm^2 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 10.5 cm^2 hole cut into a surround made of a large carpet tile, see Fig. 2. Two adjacent sides of this hole were marked with red and green tape. The yellow tape at the front of each object was lined up with either the red or the green tape for the red and green object orientations, respectively, so there was a 90° depth rotation on orientation-change trials. The object was hidden from the participant's view by card, a board, and a screen. Behind and perpendicular to the screen was a 12 cm^2 aperture through which the participant's right hand entered in order to touch the object. An infra-red beam shone across this aperture, placed so that it was broken when the participant's

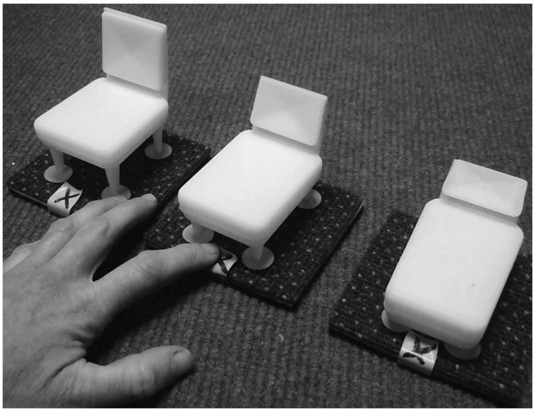


Figure 1. From left to right, the chair startpoint morph, the chair-bed midpoint morph, and the bed endpoint morph with a hand shown for scale. These three morphs comprised the chair-bed morph set which was one of the 20 experimental morph sets used in the present studies.

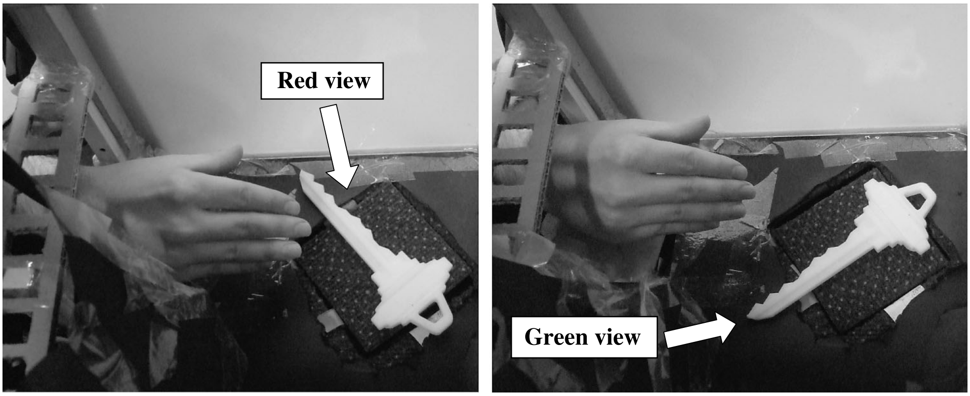


Figure 2. Photographs of the participant's right hand reaching through the aperture to touch an object. The infra-red beam is beneath the ladder-like card on the left. The hand is nearly touching the object, which is the key startpoint object from the key-sword morph set. The key is presented in the red view in the left photo and the green view in the right photo. The views are rotated 90° from each other.

hand entered the aperture. When this beam was broken a detector sent a signal to the computer controlling the experiment. People responded using a button box which was placed on the table next to their left hand.

2.1.3. 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, with one of each of these two trials presenting both objects from the same orientation and the other trial presenting the second object rotated in depth by 90° relative to the first. One group of ten morph sets was presented on 40 of the trials in a block. On these trials the first object presented was the startpoint morph. On matches, the second object presented was the same startpoint morph. On mismatches, the second object presented was the midpoint morph from the same morph set. Similar conditions were run for the second group of ten morph sets which were presented on the remaining 40 trials. However, on these trials the first object presented was the endpoint morph. Thus on matches, the second object presented was the same endpoint morph whilst on mismatches, the second object presented was the midpoint morph. The assignment of morph set to each morph set subgroup was counterbalanced across two groups of eight participants. For four of these eight people, if the first object on a trial came from the first morph set subgroup it was presented from the red orientation, and if it was from the second subgroup it was presented from the green orientation. The other four people had the reverse allocation of orientations to morph set subgroups. Further, for each of these four people, two people were given trials from the twenty morph sets in one fixed order within each sub-block (with the bottle-watering can morph set presented on the first trial), and the other two were given the same trials in the reverse order (with the bottle-watering can morph set presented on the last trial).

The experiment was run on a computer using E-Prime version 1.1 experimental presentation software (Psychology Software Tools). At the start of each trial, the experimenter placed the first object behind the screen then triggered the computer to play the words ‘go now’. This signalled to the participant that they could start to move their right hand through the aperture to touch the object behind the screen. The computer recorded when their hand broke the infrared beam across the aperture. 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 aperture. 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 words ‘go now’ again and the participant put their hand back through the aperture to touch the second object. After two seconds, the computer again played the words ‘stop now’. 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 orientation 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, single tone 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.

At the start of each trial the experimenter always moved two objects (the first object that would be presented and the object that could be the distractor on mismatches) from the storage shelf to the table next to the haptic apparatus. After the first object had been presented it was always removed from the apparatus and placed next to the distractor object before one of these two objects was put into the apparatus as the second object on a trial. These two precautions were taken to ensure that people could not determine from the sounds or movements of the experimenter whether they had been given a match or a mismatch trial. At the end of the study, people were asked whether they had used any auditory or visual information when making their responses, such as the sounds of the experimenter moving objects or seeing the objects. Everybody said that they had only used haptic information.

2.1.4. Results

ANOVAs were conducted on the mean correct reaction times (RTs) and on the percentage of errors for matches and mismatches separately. On matches, same-shape responses were correct. On mismatches, shape-change, different responses were correct. Response latencies less than 750 ms or exceeding 10 000 ms were discarded as errors (less than 1% of trials). No participants were replaced.

There was one within-participants factor, orientation change (0° or 90°) and two counterbalancing factors: the within-participants factor of morph set subgroup (whether the first object on a trial was the startpoint morph for the first subgroup of morph sets and the endpoint morph for the second subgroup of morph sets or *vice versa*) and the between-participants factor of orientation subgroup (whether the first object on a trial was presented from the red orientation for the first subgroup of morph sets and the green orientation for the second subgroup of morph sets or *vice versa*). These counterbalancing factors were not of theoretical interest so effects involving them are not reported in these and subsequent analyses. Results are reported for both by-participants (F_{p}) and by-items (F_{i}) analyses.

For same-shape matches, orientation change was significant for both RTs [$F_{\mathrm{p}}(1,14) = 32.80$, $p < 0.001$, partial $\eta^2 = 0.70$, $F_{\mathrm{i}}(1,18) = 11.13$, $p < 0.005$, partial $\eta^2 = 0.38$] and errors [$F_{\mathrm{p}}(1,14) = 10.31$, $p < 0.007$, partial $\eta^2 = 0.42$, $F_{\mathrm{i}}(1,18) = 6.85$, $p < 0.02$, partial $\eta^2 = 0.28$]. Same-orientation matches (2296 ms, 21% errors) were 191 ms faster and 11% more accurate than 90° orientation-change matches (2487 ms, 32%) (see Figs 3 and 4). Although shape-change mismatches were not the focus of this study, the results are included for completeness. Orientation change was significant for participants and marginally significant for items for RTs [$F_{\mathrm{p}}(1,14) = 7.49$, $p < 0.02$, partial $\eta^2 = 0.35$, $F_{\mathrm{i}}(1,18) = 3.66$, $p < 0.08$, partial $\eta^2 = 0.17$] but it was not significant for errors [$F_{\mathrm{p}}(1,14) = 1.94$, $p > 0.1$, partial $\eta^2 = 0.12$, $F_{\mathrm{i}}(1,18) = 1.92$, $p > 0.1$, partial $\eta^2 = 0.10$]. Same-orientation mismatches (2260 ms, 41% errors) were 87 ms faster than 90° orientation-change mismatches (2347 ms, 36%). These initial analyses revealed similar levels of orientation-sensitivity in this hard, restricted exploration time task as in the HH sequential matching task tested by Lawson (2009). Two further analyses were conducted in order to directly compare the results of Experiment 1 here with those from the hard and easy HH groups respectively from Experiment 2 of Lawson (2009).

2.1.5. *Is Orientation-Sensitivity Modulated by Exploration Time when Shape Discriminability Is Equated?*

Matches from Experiment 1 were analysed with matches from the 16 people in the hard shape discrimination HH group reported by Lawson (2009). The only difference between the two groups was that, in Experiment 1 here, people were told to stop feeling the second object after 2 s whereas in Lawson (2009) people had unlimited time to feel it and their average exploration time was much longer, at around 4 s. There was one within-participants factor, orientation change (0° or 90°), and one between-participants factor, exploration time (for the second object, either 2 s or unlimited). There were also the same two counterbalancing factors as were used in the initial analyses: morph set subgroup and orientation subgroup. Since the results for the two groups have already been reported individually, only the two effects of interest are discussed: the main effect of exploration time and the interaction of exploration time × orientation change, for match trials.

Exploration time was significant for RTs [$F_{\mathrm{p}}(1,28) = 80.24$, $p < 0.001$, partial $\eta^2 = 0.74$, $F_{\mathrm{i}}(1,18) = 714.95$, $p < 0.001$, partial $\eta^2 = 0.98$] but not for errors [$F_{\mathrm{p}}(1,28) = 0.72$, $p > 0.4$, partial $\eta^2 = 0.03$, $F_{\mathrm{i}}(1,18) = 1.56$, $p > 0.2$, partial

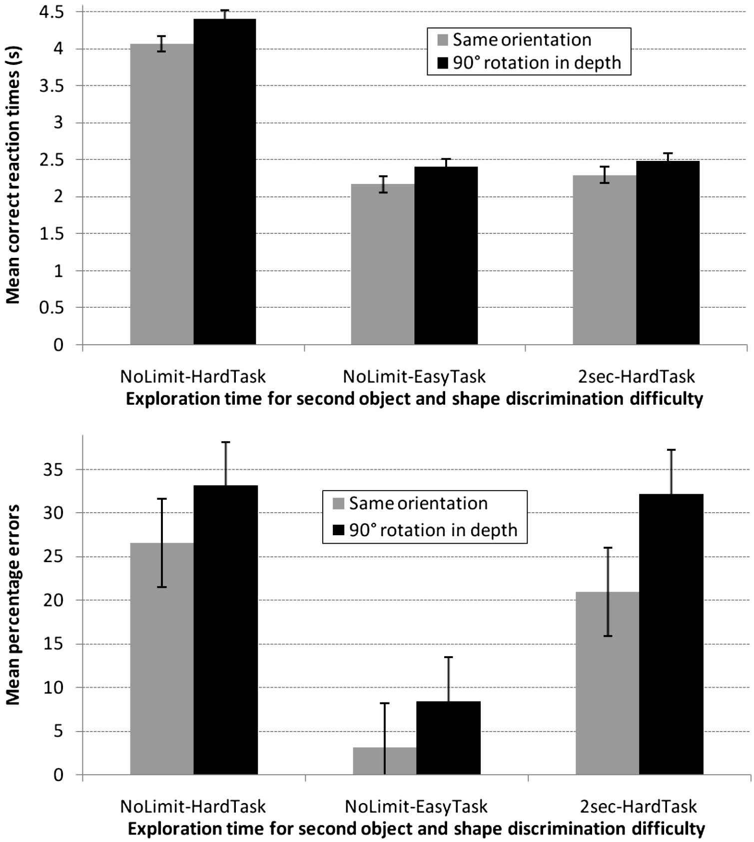
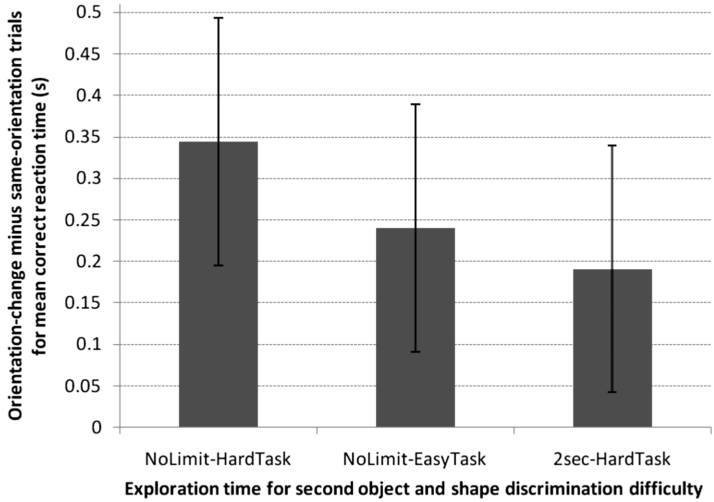


Figure 3. Mean correct RTs (above) and mean percentage errors (below) for three groups who did the same HH sequential matching task: the hard group (left) and easy group (middle) from Experiment 2 of Lawson (2009) and the hard group (right) from Experiment 1 here. There were just two differences between the three groups. First, the exploration duration of the second object was unlimited in Experiment 2 of Lawson (2009) but was restricted to 2 s in Experiment 1 here. Second, shape discrimination difficulty was greater for the two hard groups than for the easy group. Results are shown for match trials only, for same-orientation and orientation-change trials separately. Error bars show 95% within-participant confidence intervals calculated using the error term of the orientation × group interaction for an analysis including all three groups (Jarmasz and Hollands, 2009; Loftus and Masson, 1994).

$\eta^2 = 0.08$]. People given only 2 s to explore the second object (2392 ms, 27% errors) responded 1848 ms faster but similarly accurately to people given unlimited time to feel the second object (4239 ms, 30%). As expected, RTs were much faster when exploration duration was restricted. Surprisingly, though, this did not increase errors. This raises the interesting question as to why people spent so long exploring the second object, given that this did not improve their accuracy.

Most importantly, there was no evidence for the hypothesis that reducing the exploration time for the second object would increase orientation-sensitivity. The interaction of exploration time × orientation change was not significant for RTs



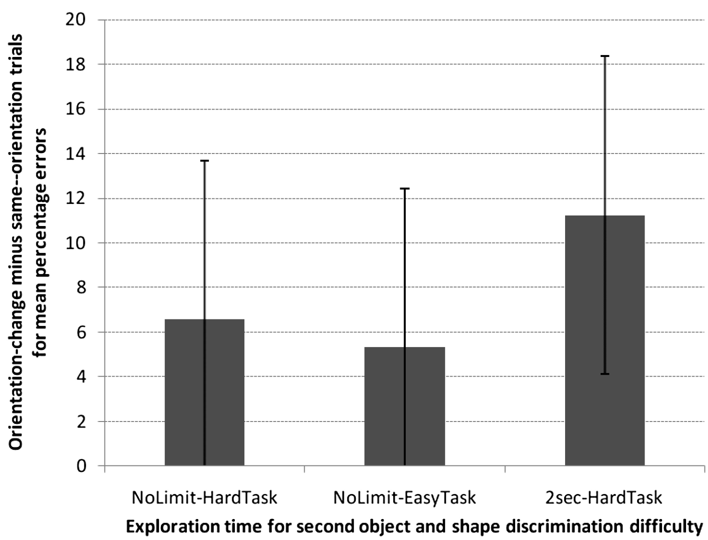


Figure 4. Mean difference between same-orientation and orientation-change matches for correct RTs (above) and percentage errors (below) for three groups who did the same HH sequential matching task: the hard group (left) and easy group (middle) from Experiment 2 of Lawson (2009) and the hard group (right) from Experiment 1 here. Error bars show 95% within-participant confidence intervals calculated using the error term for the main effect of group for an analysis including all three groups (Jarmasz and Hollands, 2009; Loftus and Masson, 1994).

for subjects though it was for items [$F_p(1,28) = 2.10$, $p > 0.1$, partial $\eta^2 = 0.07$, $F_i(1,18) = 9.78$, $p < 0.007$, partial $\eta^2 = 0.35$] and the interaction was not significant for errors [$F_p(1,28) = 0.69$, $p > 0.4$, partial $\eta^2 = 0.02$, $F_i(1,18) = 0.44$, $p > 0.5$, partial $\eta^2 = 0.02$]. Furthermore, the trend for RTs was in the opposite direction to that predicted, with a smaller same orientation advantage after 2 s exploring the second object (191 ms) than after around 4 s exploration (344 ms). For errors, the same orientation advantage was similar after 2 s (11%) and 4 s (7%) exploration.

2.1.6. Is Orientation-Sensitivity Modulated by Shape Discriminability when Exploration Time is Equated?

Matches from Experiment 1 were analysed with matches from the 16 people in the easy shape discrimination HH group reported by Lawson (2009). There were only two differences between the two groups. First, the easy group had unlimited time to feel the second object, instead of being told to stop feeling it after 2 s. Second, on mismatches they felt two completely different shaped objects (e.g., shark then cup) rather than two very similarly shaped objects (e.g., shark then fish-shark morph) so responses were fast since the task was easy. There was one within-participants factor, orientation change (0° or 90°), and one between-participants factor, shape discriminability (hard or easy). There were also the same two counterbalancing factors as were used in the initial analyses: morph set subgroup and orientation subgroup. Since the results for the two groups have already been reported individually, only the two effects of interest are reported: the main effect of shape discriminability and the interaction of shape discriminability × orientation change, for matches.

Shape discriminability was not significant for RTs [$F_{\mathrm{p}}(1,28) = 0.24$, $p > 0.6$, partial $\eta^2 = 0.01$, $F_{\mathrm{i}}(1,18) = 2.02$, $p > 0.1$, partial $\eta^2 = 0.10$] but it was significant for errors [$F_{\mathrm{p}}(1,28) = 42.89$, $p < 0.001$, partial $\eta^2 = 0.61$, $F_{\mathrm{i}}(1,18) = 113.63$, $p < 0.001$, partial $\eta^2 = 0.86$]. As expected, accuracy was much worse, by 21%, when shape discrimination was hard (2392 ms, 27% errors) than when it was easy (2288 ms, 6%). Critically, though, the two groups were well matched in terms of the time that they had to explore the second object before responding.

Most importantly, the interaction of shape discriminability × orientation change was not significant for RTs [$F_{\mathrm{p}}(1,28) = 0.39$, $p > 0.5$, partial $\eta^2 = 0.01$, $F_{\mathrm{i}}(1,18) = 1.47$, $p > 0.2$, partial $\eta^2 = 0.08$] or for errors [$F_{\mathrm{p}}(1,28) = 2.02$, $p > 0.1$, partial $\eta^2 = 0.07$, $F_{\mathrm{i}}(1,18) = 1.80$, $p > 0.1$, partial $\eta^2 = 0.09$]. The same orientation benefit was similar whether shape discrimination was hard (191 ms, 11% errors) or easy (240 ms, 5%). Thus, the effects of shape discriminability were additive with the effects of orientation, in contrast to the interaction that has been reported for visual object recognition (Lawson, 2004; Lawson and Bülthoff, 2008; Vuong *et al.*, 2009). The results are consistent with those of Lawson (2009): there was no support for the hypothesis that haptic orientation-sensitivity is influenced by the difficulty of shape discrimination.

2.1.7. Discussion

The results from Experiment 1 were clear: HH matching was easier on same-orientation compared to orientation-change trials and this orientation-sensitivity was not modulated by either the time taken to explore the second object or by the difficulty of shape discrimination. These results support the claim that haptic object recognition is mediated by orientation-specific, stored haptic object representations. Further implications of these findings will be considered in the General Discussion.

2.2. *Experiment 2*

As outlined in the Introduction, haptic orientation-sensitivity in matching studies might result from general, spatial or motor priming effects rather than indicating the use of stored, orientation-sensitive haptic representations of objects. For vision, such effects are known to influence reaching for objects (e.g., Haffenden and Goodale, 2002; Hesse *et al.*, 2008; Jax and Buxbaum, 2010; Jax and Rosenbaum, 2007, 2009; Kroliczak *et al.*, 2008). For haptic object recognition, spatial cueing may aid same-orientation matches if people preferentially explore the location that they last felt an object or the place where they last felt important, distinguishing information from an object. Alternatively, orientation-sensitivity might be due to memory of the location of the main axis of a previously explored object or to explicit recall of its orientation or to priming of the motor actions made when touching it. As detailed below, all such accounts predict that if the standard HH sequential matching task includes, interleaved within it, an orientation judgement task on an unrelated object, then this should reduce orientation-sensitivity. This prediction was tested in Experiment 2.

In Experiment 2, three objects were presented on every trial, all centred at the same location. The first and last objects were the stimuli for the standard HH sequential matching task as was used in Experiment 1. This shape change detection task was the main task. The middle object was always a real fork or spoon. People decided if the fork or spoon pointed towards or away from them in a secondary orientation judgement task. The fork and spoon were chosen because they had a clear main axis to define their orientation, they were quite flat and they were made of different materials than the main stimulus set so were easily distinguished from them. Feeling the fork or spoon served to mask any motor actions which people had made to the first object. Thus, in contrast to same-orientation trials in the standard HH sequential matching task, same-orientation trials did not benefit from the immediate repetition of motor actions. Furthermore, the location of the front of the fork/spoon and the orientation of its main axis of elongation was always the same as that of the final object. As a result, if people tended to return their hand to the spatial location that they had previously felt important information (the front of the fork/spoon) or if people expected the main axis of an object to match that of the previous object that they had felt then feeling the fork/spoon should benefit same-orientation and orientation-change trials equally. People were explicitly informed that the fork/spoon would always have the same orientation as the final object and they were told that this information might help them to identify the final object.

In Experiment 2, no attempt was made to distinguish between the various alternative hypotheses about priming of an object's position in space, the location of its key features or its main axis, motor action priming or explicit orientation cueing strategies. All of these accounts predicted that doing the secondary orientation judgement task should weaken or eliminate orientation-sensitivity in the main shape change detection task. The goal of Experiment 2 was to contrast the prediction from this class of hypotheses with that of an explanation based on priming of object-specific haptic stored representations. Only this latter account predicted that haptic orientation-sensitivity would not be influenced by the secondary task. Performance in Experiment 2 was compared to that of a matched group from Lawson (2009) who did the same sequential HH shape matching task with the same stimuli but who did not do the secondary orientation judgement task.

2.2.1. Participants

There were 16 participants aged 18–20, all but one of whom were right-handed. Participants were undergraduate students from the University of Liverpool, U.K., who took part in the study for course credit.

2.2.2. Materials and Apparatus

These were identical to Experiment 1. In addition, a real spoon and a real fork were glued onto 10 cm^2 bases made of carpet tile with yellow tape marking the middle of one side of the base. The spoon and fork were oriented so that their front end was next to the yellow tape. The other, handle end was identical for the spoon and fork.

2.2.3. Design and Procedure

The design was identical to Experiment 1 except for the following four points. A secondary orientation judgement task was interleaved within the main shape-matching task. The shape-matching task was made easier by using a larger shape change on mismatches. There was no ‘stop now’ for the final object, so people had unlimited time to explore the final object. Finally, the initial instructions were extended to inform people about the relation between the orientation of the spoon/fork and the final object. These changes are explained in detail below.

After the initial object had been removed from the apparatus, either the spoon or the fork was placed into the apparatus at the same orientation as the final object would be presented. For example, for a chair–chair orientation-change match trial with the spoon cue, if the chair was initially presented at the red orientation then the spoon would be presented at the green orientation and finally the chair would be presented again, but now at the green orientation. Once the spoon/fork was in position the experimenter triggered the computer to play the words ‘go now’ and the participant put their hand into the aperture to touch it. Half the trials presented the spoon and half the fork, with the object alternating after a maximum of two trials. People responded verbally by either saying ‘me’ or ‘away’ to indicate whether the spoon or the fork pointed towards or away from themselves, respectively. People were not given feedback about their performance on the orientation judgement task. The experimenter coded the participant’s response then removed the spoon/fork and put the final object behind the screen. Participants were allowed to explore this object as long as they wished.

On matches, the final object was identical to the first object, as in Experiment 1. However, on mismatches the final object was the other endpoint morph from the same morph set as the first object, rather than the midpoint morph as in Experiment 1. This meant that the shape discrimination task was easier than in Experiment 1 because there was a larger shape change on mismatches. Finally, before the experiment began, people were explicitly told that the spoon or fork would have the same orientation as the final object. They were informed that this should help them to do the same/different shape change detection task by cueing them about the position of the final object.

2.2.4. *Results*

Responses were accurate on the secondary orientation judgement task, with fewer than 0.5% errors. These responses were not analysed further. ANOVAs were conducted on the mean correct RTs and on the percentage of errors for matches and mismatches separately for the main shape change detection task. On matches, same-shape responses were correct. On mismatches, shape-change, different responses were correct. Response latencies less than 750 ms or exceeding 10 000 ms were discarded as errors (less than 1% of trials were removed). No participants were replaced. There was one within-participants factor: orientation change (0° or 90°). There were also the same two counterbalancing factors as in Experiment 1: morph set subgroup and orientation subgroup. These counterbalancing factors were not of theoretical interest so effects involving them are not reported in these and subsequent analyses.

For same-shape matches, orientation change was significant for both RTs [$F_p(1,14) = 6.15$, $p < 0.03$, partial $\eta^2 = 0.31$, $F_i(1,18) = 8.39$, $p < 0.02$, partial $\eta^2 = 0.32$] and errors [$F_p(1,14) = 9.00$, $p < 0.02$, partial $\eta^2 = 0.39$, $F_i(1,18) = 9.31$, $p < 0.01$, partial $\eta^2 = 0.34$]. Same-orientation matches (3196 ms, 10% errors) were 406 ms faster and 8% more accurate than 90° orientation-change matches (3602 ms, 18%) (see Figs 5 and 6). Although shape-change mismatches were not the focus of this study, the results are included for completeness. Orientation change was marginally significant for participants but was not significant for items for RTs [$F_p(1,14) = 4.08$, $p < 0.07$, partial $\eta^2 = 0.23$, $F_i(1,18) = 0.74$, $p > 0.4$, partial $\eta^2 = 0.04$] and it was not significant for errors [$F_p(1,14) = 0.09$, $p > 0.7$, partial $\eta^2 = 0.01$, $F_i(1,18) = 0.00$, $p > 0.9$, partial $\eta^2 = 0.00$]. Same-orientation mismatches (3108 ms, 17% errors) were 115 ms faster but no more accurate than orientation-change mismatches (3223 ms, 17%).

These initial analyses established that HH sequential matches are sensitive to orientation changes even when people know the orientation of the final object before it is presented and even when they make hand movements to another (fork/spoon) object in-between feeling the two objects for the main sequential matching task. Further analyses were then conducted to investigate whether orientation-sensitivity was weaker in Experiment 2, with a secondary orientation judgement task, compared to when people only did the standard HH sequential matching task.

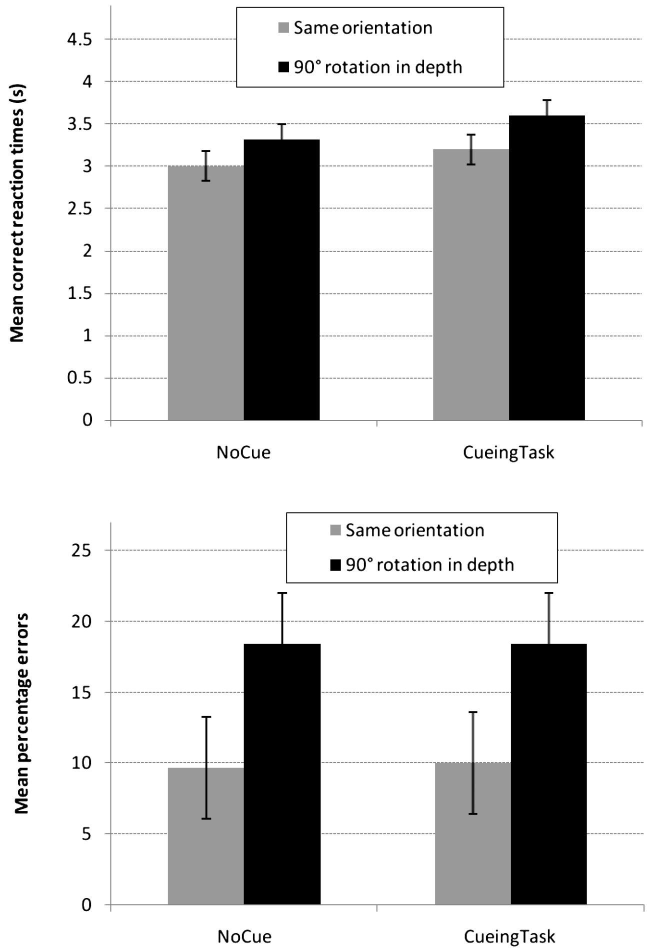


Figure 5. Mean correct RTs (above) and mean percentage errors (below) for two groups who did the same HH sequential matching task: on the left, the uncued medium group from Experiment 2 of Lawson (2009) and on the right the cued medium group from Experiment 2 here. The only difference between the two groups was that the latter group did a secondary orientation judgement (cueing) task as well as the main shape change detection matching task. Results are shown for match trials only, for same-orientation and orientation-change trials separately. Error bars show 95% within-participant confidence intervals calculated using the error term of the orientation × cueing interaction (Jarmasz and Hollands, 2009; Loftus and Masson, 1994).

2.2.5. Is Orientation-Sensitivity Modulated by Doing a Secondary Cueing Task?

The results for matches from Experiment 2 were compared to matches for the 16 people in the medium shape discrimination HH group reported by Lawson (2009). Both groups did the same shape change detection task with the same stimuli and apparatus. The only difference was that the latter group did not do the interleaved spoon/fork orientation judgement task. Note that this medium discrimination group differed from both of the groups from Lawson (2009) which were tested in the

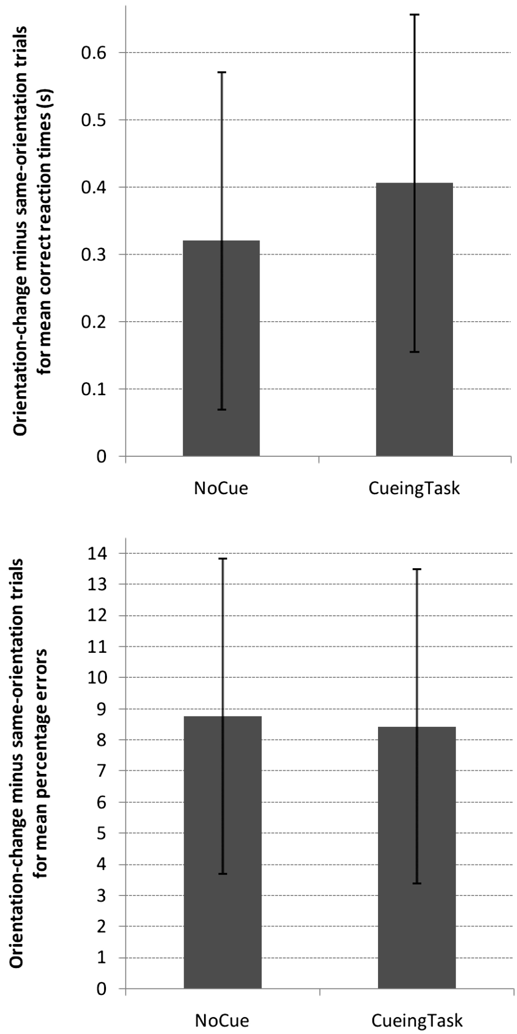


Figure 6. Mean difference between same-orientation and orientation-change matches for correct RTs (above) and percentage errors (below) for two groups doing the same HH sequential matching task: on the left, the uncued medium group from Experiment 2 of Lawson (2009) and on the right the cued medium group from Experiment 2 here. Error bars show 95% within-participant confidence intervals calculated using the main effect of cueing (Jarmasz and Hollands, 2009; Loftus and Masson, 1994).

two joint analyses reported in Experiment 1. This medium group did the same, moderately difficult shape discrimination task as the people in Experiment 2 here. This analysis investigated whether haptic orientation-sensitivity was modulated by doing a secondary orientation judgement task when shape discriminability in the main matching task was held constant. There was one within-participants factor, orientation change (0° or 90°), and one between-participants factor, secondary task (whether people did the secondary spoon/fork orientation judgement task). There were also the same two counterbalancing factors as were used in the initial analyses: morph set subgroup and orientation subgroup. Since the results for the two groups have already been reported individually, only the two effects of interest are reported: the main effect of secondary task and the interaction of secondary task × orientation change, for matches.

The secondary task was significant for items only for RTs [$F_p(1,28) = 0.59$, $p > 0.4$, partial $\eta^2 = 0.02$, $F_i(1,18) = 10.74$, $p < 0.005$, partial $\eta^2 = 0.37$]. It was not significant for errors [$F_p(1,28) = 0.00$, $p > 0.9$, partial $\eta^2 = 0.00$, $F_i(1,18) = 0.01$, $p > 0.9$, partial $\eta^2 = 0.00$]. Doing a secondary orientation judgement task (3399 ms, 14% errors) produced somewhat slower matching responses compared to when there was no secondary task (3159 ms, 14%).

Most importantly, the interaction of secondary task × orientation change was not significant for either RTs [$F_p(1,28) = 0.24$, $p > 0.6$, partial $\eta^2 = 0.01$, $F_i(1,18) = 0.01$, $p > 0.9$, partial $\eta^2 = 0.00$] or errors [$F_p(1,28) = 0.01$, $p > 0.9$, partial $\eta^2 = 0.00$, $F_i(1,18) = 0.01$, $p > 0.9$, partial $\eta^2 = 0.00$]. The same orientation advantage was similar whether there was a secondary task (406 ms, 8%) or not (320 ms, 9%). Specifically, there was no evidence that doing the secondary task reduced orientation-sensitivity. There was, therefore, no support for the hypothesis that haptic orientation-sensitivity results from general spatial cueing or motor priming.

2.2.6. Discussion

People in Experiment 2 revealed clear orientation-sensitivity in the main HH shape-change detection task despite having to also do an interleaved, secondary orientation judgement task. Critically, this orientation-sensitivity was as strong as that of a matched group tested by Lawson (2009) who did the same HH matching task but who did not do the secondary task. These results provide evidence against a range of hypotheses which attribute the haptic orientation-sensitivity found in matching tasks as being due to cueing of the spatial location of an object or of its important parts or to the orientation of its main axis or priming of motor actions. The present finding instead supports the conclusion that haptic orientation-sensitivity is caused by the use of stored, object-specific haptic representations.

This conclusion is consistent with the finding of orientation-sensitivity reported by Craddock and Lawson (2008) for a long-term old/new haptic object recognition memory task. Here, the two presentations of a given object were separated by several minutes and many other objects were explored during this intervening period. Here, too, the orientation-sensitivity observed cannot be explained by general (rather than object-specific) priming effects. In addition, Craddock and Lawson (2010) found similar orientation-sensitivity in a sequential matching task testing different, novel 3D objects when the inter-stimulus interval was increased from 3 to 15 s, again suggesting that haptic processing uses stable, orientation-specific object representations.

3. General Discussion

The two experiments reported here investigated the cause of the orientation-sensitivity that has been found for haptic as well as visual object processing in order to assess whether object constancy is achieved in the same way across both modalities. Specifically, the studies tested whether this orientation-sensitivity implicates the use of orientation-specific haptic object representations. In Experiment 1, people were restricted in how long they could haptically explore an object. In Experiment 2, a secondary orientation judgement task was interleaved within the main shape change detection task. Neither manipulation reduced orientation-sensitivity in a sequential matching task. Thus haptic orientation-sensitivity remains stable across variation in the difficulty of shape discrimination, exploration duration and the availability of cues to the location and orientation of an upcoming object. These results suggest that differences between visual and haptic orientation-sensitivity are not caused by variation in the manner of exploration and information acquisition across the two modalities. Recent evidence suggests that visual and haptic perceptual spaces are very similar (Cooke *et al.*, 2007; Gaissert *et al.*, 2010). Nevertheless, the present findings indicate that distinct processes and representations are involved in visual compared to haptic object recognition. This conclusion is consistent with recent evidence that distinct, modality-specific reference frames are used for visual *versus* haptic object representations (Volcic *et al.*, 2010).

These findings provide crucial support for the claim that, in contrast to visual object recognition, haptic orientation-sensitivity is not influenced by the difficulty of shape discrimination (Lawson, 2004, 2009; Lawson and Bülthoff, 2008; Vuong *et al.*, 2009). In particular, Experiment 1 found no influence of shape discriminability even when exploration time was matched across hard and easy discrimination tasks. This result provides evidence against the claim that shared processes and representations are involved in visual and haptic object recognition. It is important to note that varying shape discriminability has a powerful effect on haptic as well as visual accuracy (see Fig. 3). Thus, the lack of an interaction between orientation-sensitivity and shape discriminability cannot be trivially explained as being due to discriminability not being encoded by haptics (as would be the case for other, visual-only cues such as colour). Instead, shape discriminability appears to influence haptics in a very different way to vision.

There was also no evidence that general spatial cueing and priming effects caused the haptic orientation-sensitivity observed in the main HH shape change detection task. It is important to emphasise that this does not mean that such cueing never influences haptic object recognition. Indeed this is unlikely given that priming and cueing effects can be important for vision (e.g., Haffenden and Goodale, 2002; Hesse *et al.*, 2008; Jax and Buxbaum, 2010; Jax and Rosenbaum, 2007, 2009; Kroliczak *et al.*, 2008). The aim of Experiment 2 was to test whether cueing effects could explain the haptic orientation-sensitivity observed in Lawson (2009). All stimuli were similar in size (scaled to be approximately hand sized; see Fig. 1) and were centred at the same location within a small area, and the hand moved towards the object through a narrow aperture (see Fig. 2). There was, therefore, little trial-to-trial variation in the optimal initial hand movement to touch an object. Cueing is likely to be much more important if objects of varying size are presented at different locations within a large area. In such cases, cueing effects may dominate performance because, unlike vision, haptic exploration is necessarily serial, so finding an object can be time-consuming.

In conclusion, these results suggest that, despite superficial similarities in performance on object recognition tasks across the modalities, visual and haptic shape processing involves modality-specific, stored object representations that are orientation-sensitive. The basic differences in how stimuli are typically explored visually *versus* haptically makes this claim difficult to test. However, the results reported here did not support alternative accounts of haptic orientation-sensitivity as being due to variation in exploration time or to general spatial or orientation cueing effects.

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