

A Comparison of the Effects of Depth Rotation on Visual and Haptic Three-Dimensional Object Recognition

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A sequential matching task was used to compare how the difficulty of shape discrimination influences the achievement of object constancy for depth rotations across haptic and visual object recognition. Stimuli were nameable, 3-dimensional plastic models of familiar objects (e.g., bed, chair) and morphs midway between these endpoint shapes (e.g., a bed–chair morph). The 2 objects presented on a trial were either both placed at the same orientation or were rotated by 90° relative to each other. Discrimination difficulty was increased by presenting more similarly shaped objects on mismatch trials (easy: bed, then lizard; medium: bed, then chair; hard: bed, then bed–chair morph). For within-modal visual matching, orientation changes were most disruptive when shape discrimination was hardest. This interaction for 3-dimensional objects replicated the interaction reported in earlier studies presenting 2-dimensional pictures of the same objects (Lawson & Bühlhoff, 2008). In contrast, orientation changes and discrimination difficulty had additive effects on within-modal haptic and cross-modal visual-to-haptic matching, whereas cross-modal haptic-to-visual matching was orientation invariant. These results suggest that the cause of orientation sensitivity may differ for visual and haptic object recognition.

Keywords: visual, haptic, object recognition, depth rotation, object constancy

Visual object constancy is the ability to consistently identify stimuli despite variation in their appearance. A common cause of such variation is an orientation change from one viewing instance to the next (see Lawson, 1999, for a review). A primary focus of researchers investigating object recognition has been to understand how visual object constancy is achieved. In contrast, little research has examined how the haptic system recognizes three-dimensional objects across changes in perceptual input. The present studies investigated the achievement of haptic object constancy by testing the sensitivity of haptic object recognition to changes in the orientation in depth at which a given object was presented. Depth rotations have been found to be particularly disruptive to achieving visual object constancy in comparison with changes of size, position, and illumination. Furthermore, as discussed below, the visual system is especially sensitive to orientation changes in depth when shape discrimination is difficult (Lawson & Bühlhoff, 2008). As reviewed below, there is now evidence from a range of different methodologies suggesting that common, multimodal object representations are involved in visual and haptic object recognition. The present studies therefore tested whether a similar interaction be-

tween the effects of depth rotation and shape discriminability would be observed for haptic as for visual object recognition. If these two factors have similar effects on haptic as on visual object recognition, this would be consistent with the hypothesis that the two systems access the same perceptual representations.

Evidence for Common Perceptual Representations Involved in Visual and Haptic Object Recognition

There are several lines of evidence that have demonstrated similarities between visual and haptic object recognition. These results suggest that, for object recognition, there are closer links between these two modalities than occur between other pairs of sensory modalities, presumably due to the greater importance of shape information to vision and haptics. For example, Cooke, Jäkel, Wallraven, and Bühlhoff (2007) found that both visual and haptic similarity estimates were influenced by shape and texture for three-dimensional novel objects presented at a fixed orientation. However, their multidimensional scaling analyses revealed that texture had more influence on perceived similarity for haptic than for visual presentation (see also Lakatos & Marks, 1999). Shape dominated texture for visual judgments of similarity, whereas shape and texture were about equally important for haptic judgments. Nevertheless, the same perceptual map could account for visual, haptic, and visual-plus-haptic ratings, suggesting that information from both modalities may converge or overlap in multimodal object representations.

Because within-modal (and especially visual–visual) object matching is often superior to cross-modal matching, it seems unlikely that there is full perceptual equivalence across visual and haptic representations (Garbin, 1988, 1990; Lacey & Campbell, 2006). Several behavioral studies, however, have demonstrated efficient cross-modal transfer of information between vision and

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haptics (Easton, Srinivas, & Greene, 1997; Reales & Ballesteros, 1999), and this has led many to suggest that the same or very similar representations mediate visual and haptic object recognition (Heller & Ballesteros, 2006). For example, Easton, Greene, and Srinivas (1997) tested naming and old–new recognition memory for visually and haptically presented familiar objects. They found substantial within-modal and cross-modal priming of naming and accurate within-modal and cross-modal recognition. Likewise, Norman, Norman, Clayton, Lianekhammy, and Zielke (2004) tested visual, haptic, and cross-modal matching with plastic models of 12 bell peppers. Cross-modal performance was as accurate as haptic–haptic matching, suggesting that three-dimensional object recognition is similar for visual and haptic inputs.

The conclusion that visually and haptically presented three-dimensional objects are represented in a similar way is consistent with the results of several recent imaging studies, which have compared visual and haptic object processing. These have found that common areas such as the lateral occipital tactile–visual region are activated during both visual and haptic object recognition (e.g., Amedi, Jacobson, Hendler, Malach, & Zohary, 2002; James et al., 2002; Peltier et al., 2007; Pietrini et al., 2004; Prather, Votaw, & Sathian, 2004; see Amedi, von Kriegstein, van Atteveldt, Beauchamp, & Naumer, 2005, for a review).

Therefore, converging evidence from diverse methodologies (multidimensional scaling of similarity ratings, psychophysical experiments, and imaging studies) suggests that there is substantial overlap between visual and haptic object recognition. If these two modalities access the same perceptual representations, then factors known to influence visual object recognition should similarly influence haptic object recognition. This was investigated in the present studies by testing whether a similar interaction between the effects of orientation sensitivity and shape discriminability occurred for haptic object recognition as has been demonstrated previously for visual object recognition (Lawson, 2004b; Lawson & Bülthoff, 2008).

Orientation Sensitivity and Shape Discriminability in Visual Object Recognition

Our visual system is highly efficient at abstracting away from task-irrelevant variation in the input to identify and categorize objects. Object recognition is usually both fast and accurate despite changes in the size, position, orientation, and lighting of an object (Lawson, 1999). However, there is often a cost to the achievement of object constancy in either the speed or the accuracy of processing. For example, the identification of a familiar object is primed more if it is seen a second time from the same or a similar orientation as on its initial presentation than if it is seen at different orientations at priming and at test (e.g., Hayward, 1998; Lawson & Bülthoff, 2006; Lawson, Bülthoff, & Dumbell, 2003; Lawson & Humphreys, 1996, 1998, 1999; Lawson, Humphreys, & Watson, 1994; Srinivas, 1995; Thoma & Davidoff, 2006; Vuilleumier, Henson, Driver, & Dolan, 2002). The results of these priming and other studies suggest that the stored visual representations of objects are orientation sensitive.

One critical factor in determining the efficiency with which the visual system achieves object constancy over depth rotation is the difficulty of shape discrimination (Lawson, 2004b; Lawson &

Bülthoff, 2008; but see Hayward & Williams, 2000). A number of studies have found that orientation sensitivity is greater when shape discrimination is more difficult. This has been observed for the recognition and the categorization of both novel and familiar objects. However, all of these studies presented three-dimensional objects as two-dimensional depictions on a computer monitor. The availability of extra depth cues, such as stereoscopic information may reduce orientation sensitivity (Bennett & Vuong, 2006; Burke, 2005; Humphrey & Khan, 1992). The present research investigated whether the same interaction between orientation sensitivity and shape discriminability occurred for the visual recognition of three-dimensional objects as for two-dimensional pictures of the same objects. Objects were presented in visual–visual sequential matching tasks with a similar design to that of Lawson (2004b) and Lawson and Bülthoff (2008).

Orientation Sensitivity and Shape Discriminability in Haptic Object Recognition

Research into the achievement of haptic object constancy over orientation changes has been relatively neglected in comparison with the amount of research investigating orientation sensitivity in visual object recognition. However, four recent studies have now investigated the effect of orientation on the haptic identification of three-dimensional objects (Craddock & Lawson, 2008; Forti & Humphreys, 2005; Lacey, Peters, & Sathian, 2007; Newell, Ernst, Tjan, & Bülthoff, 2001). Despite many differences across these studies in the tasks, stimuli, and participants involved, all of the studies reported evidence that haptic object recognition is orientation sensitive. Furthermore, Heller et al. (2006) reported orientation sensitivity for the haptic recognition of two-dimensional pictures of three-dimensional, novel objects. However, because an inconsistent pattern of orientation sensitivity has been reported in this research and the methodology used varied widely across the four studies, it is not yet clear what overall conclusions can be drawn regarding the orientation sensitivity of haptic object recognition.

Forti and Humphreys (2005) reported a single case study in which their patient haptically studied an object with both hands. She then had to decide which item it was from six visually presented objects shown at canonical orientations. Her cross-modal matching was more accurate if the study object was presented haptically at a canonical rather than a noncanonical orientation for both familiar objects, such as scissors and a watch, and for plasticine models of those objects. However, within-modal matching was not tested, so differences between visual and haptic matching could not be compared. Furthermore, the orientation sensitivity observed may have been due to problems in haptically encoding the noncanonically oriented objects rather than reflecting the orientation sensitivity of stored object representations.

Newell et al. (2001) compared recognition for objects made of vertical stacks of six identical, plastic blocks, which were fixed on stands. They found orientation sensitivity for both within-modal and cross-modal visual and haptic recognition. Within-modal visual and haptic old–new recognition was more accurate when objects were presented at the same orientation at study and at test as compared with instances in which the object was rotated by 180° in depth, even though both hands could freely explore the object in the haptic task. In contrast, cross-modal recognition was

more accurate following a 180° orientation change from study to test. In their third experiment, an occluder permitted exploration of one side of objects only. There was no effect of an orientation change from haptic study to haptic test, but overall accuracy was greater when the object's unoccluded surface was at the back during study. Thus, an orientation change from study to test did not harm performance when the same surface was explored in both instances. This suggests that it was orientation-sensitive shape information that was being primed in these earlier studies, not the specific motor interactions made by people when they haptically explored the objects. People tended to code haptic information from the back of objects and to code visual information from the front, so orientation changes reduced within-modal but improved cross-modal performance. In both cases, performance was worse when different information was accessed from study and test presentations.

However, Newell et al.'s (2001) results may not generalize to more diverse and naturalistic stimuli. The global shape and the component parts of their objects were identical, with only the spatial relations between the parts differing. Shape discrimination in their task was at least as hard as in subordinate-level identification. In addition, the front and back orientations of Newell et al.'s block objects had to be arbitrarily assigned. In contrast, most familiar objects can be oriented along a front-back axis, and different orientations are often associated with distinctively shaped parts. For example, a dog has a main axis of elongation from its head at the front to its tail at the back. Furthermore, for Newell et al.'s objects, information from the front was redundant with information from the back, so people did not need to explore the whole object to succeed at the task. Indeed, people may have used strategies, such as verbally encoding the direction that the blocks protruded and may have only tried to encode a single surface of the object. If so, this could explain why performance was worse following an orientation change (as the verbal description of the front and back of the objects would differ) without needing to posit the involvement of orientation-sensitive object representations. The present studies presented a wide range of familiar objects. Here, verbal coding would probably reduce orientation effects, as people could match an object to its orientation-invariant label (e.g., "chair").

Lacey, Peters, and Sathian (2007) used a similar task and stimuli to those of Newell et al. (2001) and also found orientation sensitivity for within-modal visual and haptic object recognition. However, contrary to Newell et al., they did not find a significant benefit for orientation changes on cross-modal recognition, only a nonsignificant trend toward a same-orientation benefit. Lacey et al. suggested that the discrepancy between their cross-modal results and those of Newell et al. occurred because Newell et al. presented objects oriented with one side facing directly toward the participant, whereas Lacey et al. presented objects at oblique orientations. The near face of Newell et al.'s objects were therefore harder to explore haptically than other faces, so their results may have been an artifact of biomechanical constraints. However, Lacey et al.'s cross-modal results are also inconsistent with the cross-modal, same-orientation benefit of the patient reported by Forti and Humphreys (2005).

Finally, Craddock and Lawson (2008) examined the orientation sensitivity of object recognition for real exemplars of haptically familiar categories of everyday objects, such as forks, glasses, and

staplers. The same set of objects was haptically explored in two blocks by blindfolded participants using both hands. With a speeded naming task, there was substantial, but orientation-invariant, priming. Priming was no greater for objects presented at the same orientation in both blocks compared with objects rotated by 90° or 180° in depth across blocks. In contrast, old-new recognition memory was better for objects presented at the same orientation at study and test as compared with situations in which there was an orientation change across blocks. The orientation sensitivity found in the haptic recognition task replicated that reported for within-modal haptic recognition by Lacey, Peters, and Sathian (2007) and Newell et al. (2001), but the orientation invariance found in the priming task did not.

Two factors in combination may have caused this latter, discrepant result. First, implicit priming tasks (particularly with longer term priming lasting several minutes and with many intervening items, as in Craddock and Lawson's, 2008, experiment) typically produce weaker effects than do explicit recognition tasks. Implicit tasks are therefore usually less reliable measures of an independent variable and are less likely to detect significant effects (Buchner & Brandt, 2003; Buchner & Wippich, 2000; Lawson, 2004a; Meier & Perrig, 2000). Illustrating this point, for studies with a similar design to that conducted by Craddock and Lawson (2008), orientation-sensitive priming of picture naming was reported by Lawson and Humphreys (1998) but not by Biederman and Gerhardstein (1993). Second, the real objects that Craddock and Lawson (2008) presented had many orientation-invariant cues to identity, such as texture, size, and thermal conductivity. Effects of orientation changes may have been relatively weak in Craddock and Lawson's studies if participants used such features to aid their haptic recognition. In contrast, the novel stimuli tested by Lacey, Peters, and Sathian (2007) and Newell et al. (2001) did not differ with respect to these orientation-invariant features. Forti and Humphreys (2005) tested cross-modal matching for which such orientation-invariant information would be less useful than for within-modal, haptic-haptic matching, as the visual and haptic systems differ in the orientation-invariant information that each can extract. In combination, the availability of orientation-invariant cues and the use of a relatively unreliable implicit task reduced the likelihood of detecting orientation sensitivity in Craddock and Lawson's name priming study.

Overall, these studies suggest that there is a same-orientation benefit for within-modal haptic object recognition, whereas cross-modal haptic-visual object recognition may not be orientation sensitive, at least for nonaccidental orientations. However, the many differences across the four studies, the limited manipulation of factors, and some problems of interpretation mean that these conclusions are necessarily tentative. The present study tested tightly controlled stimuli with a widely used task within visual recognition research and investigated both within-modal and cross-modal matching. First, a diverse set of stimuli were presented that had the same shape as familiar objects (unlike Lacey, Peters, & Sathian, 2007; Newell et al., 2001). Orientation-invariant cues to identity, such as color and compliance, were kept constant across all stimuli (unlike Craddock & Lawson, 2008; Forti & Humphreys, 2005), forcing people to rely on shape for identification. This allowed the information potentially available from visual and haptic presentation to be closely matched. Second, stimuli presented visually and haptically were tested with the same appa-

ratus, objects, and task (unlike Craddock & Lawson, 2008; Forti & Humphreys, 2005). Third, an object–object matching task was used with a much shorter priming interval (several seconds rather than minutes) between the first and second presentation of a given object (unlike Craddock & Lawson, 2008) to try to increase sensitivity to effects of orientation. Fourth, the difficulty of shape discrimination was systematically manipulated across different groups of people. The interaction between orientation sensitivity and shape discriminability found for visual object recognition (Lawson, 2004b; Lawson & Bühlhoff, 2008) has not yet been examined for haptic object recognition. The research reviewed above has revealed superficial similarities across visual and haptic object recognition. However, this may not reflect any underlying similarity in the representations used by the two modalities. It is important to investigate the effects of additional factors that might differentially influence performance dependent on input modality. Observing the influence of the difficulty of shape discrimination in modulating the level of orientation sensitivity provides an additional means of comparing modality-specific effects on object recognition. Note, however, that the interpretation of comparisons across studies that manipulate the modality of stimulus presentation is not straightforward. A discussion of the nature of the difficulties involved in drawing conclusions and a number of alternative accounts of the results of the present studies are presented in the General Discussion and elsewhere below.

Five studies are reported in this article. All used the same three-dimensional plastic objects. These stimuli comprised sets of three morphs, which spanned the shape-space between typical exemplars of two familiar, nameable categories of objects (e.g., chair, chair–bench, and bench; see Figures 1 and 2). Lawson and Bühlhoff (2008) found that for pictures of these objects the first, start-point morph was usually given one name (e.g., 98% of naming responses were “chair”); the final, endpoint morph was normally given a different name (e.g., 98% “bench” responses); and the midpoint morph was typically identified with an approximately equal mix of the start-point and endpoint names (e.g., 46% “chair” and 47% “bench” responses).

Experiment 1 tested the accuracy with which blindfolded people could name the plastic objects following unrestricted haptic exploration. Although important haptic cues, such as texture and size were absent, people could identify most of these objects as belonging to familiar, basic-level categories. Experiments 2–5 all used the same sequential object–object matching task and the same apparatus in order to investigate the pattern of orientation sensitivity across within-modal and cross-modal matching and any interactions with the effects of varying the difficulty of shape discrimination. Experiment 2 tested within-modal haptic–haptic (HH) matching, and Experiment 3 tested within-modal visual–visual (VV) matching. Experiment 4 tested cross-modal visual-to-haptic (VH) matching, and Experiment 5 tested cross-modal haptic-to-visual (HV) matching. In all four studies, object orientation was manipulated within participants. Performance on match trials, when an object was presented from the same orientation twice, was compared with that when an object was rotated by 90° from its first to its second presentation. Shape discrimination was manipulated between participants by varying the difficulty of detecting a shape change on mismatch trials. Discrimination was easy if two completely different shaped objects were presented on mismatches (e.g., shark, then cup) and hard if two very similarly

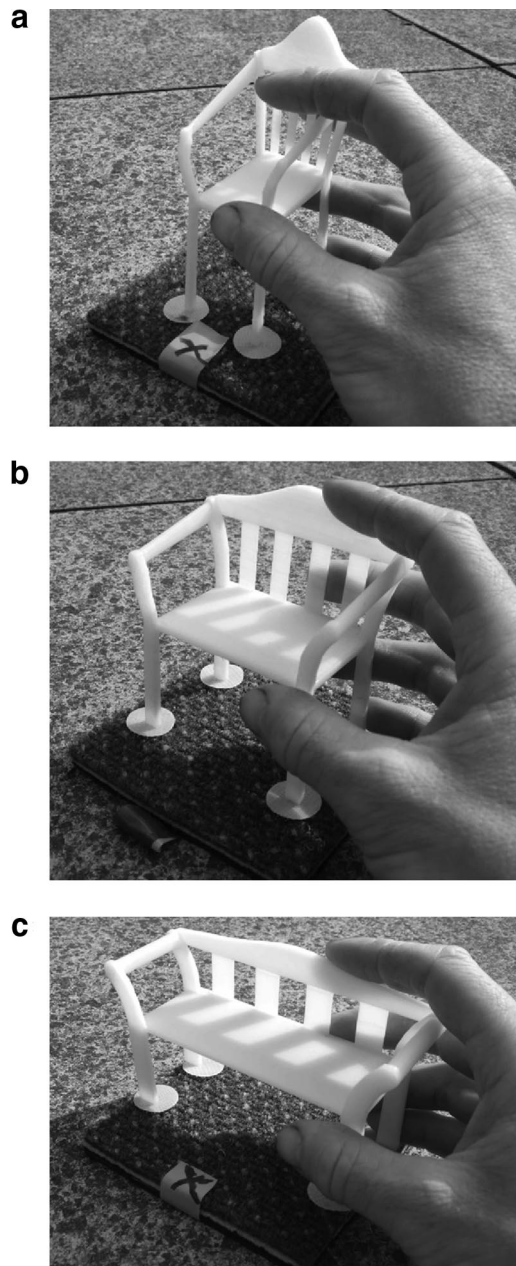


Figure 1. A hand touching (a) the chair start-point morph, (b) the chair–bench midpoint morph, and (c) the bench endpoint morph. Together these three morphs comprised the chair–bench morph set, which was one of the 20 experimental morph sets used in the present studies.

shaped objects were presented on mismatches (e.g., shark, then shark–fish morph). Orientation sensitivity was greater when shape discrimination was harder for VV but not HH or VH matching, whereas VH matching was orientation invariant.

Experiment 1

Experiment 1 tested whether people could name the set of three-dimensional morphed objects presented haptically. Klatzky,



Figure 2. Examples of the 20 morph sets. The middle object in each trio is the midpoint morph.

Lederman, and Metzger (1985) found that blindfolded people could efficiently identify everyday objects by touch alone. Their untrained participants could name 100 familiar objects with 96% accuracy. Most objects were named in 2 s, with only 6% of responses taking over 5 s. However, Klatzky et al. (1985) gave people real objects to recognize that had multiple cues to identity, such as size, texture, and thermal conductivity. In subsequent studies, Klatzky, Loomis, Lederman, Wake, and Fujita (1993) found that familiar object recognition was much worse when some of these cues were removed. They restricted haptic exploration by having participants wear thick gloves or by limiting the number of fingers contacting the object. Similarly, Lederman and Klatzky (2004) reported naming accuracy of just 40% and responses taking around 80 s when participants had to explore objects using a rigid probe or with a rigid sheath on their finger.

These studies by Klatzky and colleagues (Klatzky et al., 1985, 1993; Lederman & Klatzky, 2004) all tested real, familiar three-dimensional objects, and they reduced haptic access to object information by preventing people from exploring the object normally with their bare hands. Furthermore, informative size, texture, and material cues may have remained accessible when gloves or a probe were used to explore objects. Experiment 1 used a complementary approach: People could use their normal haptic exploration strategies, but nonshape cues were removed from the stimuli by the use of models of familiar objects, which had no useful information about size, material, texture, or weight.

The morphs of familiar objects tested here varied only in shape. All other factors were standardized and nonrealistic. The morphs were scaled to be approximately hand sized and were all made of a rigid plastic with the same surface texture, temperature, and compliance. Because the morphs were scaled, hollow, and plastic, their weight bore little relation to the weight of real exemplars of the object category that they represented. Furthermore most of the objects that Klatzky et al. (1985) used, such as carrot, wallet, safety pin, and tea bag, would have been haptically familiar to their participants. In contrast, many of the categories used in the present studies, such as giraffe, shark, and submarine, would have been haptically novel to people, although people may have haptically

explored models of these objects, such as children's toys. Finally, shape discriminability was not systematically manipulated in Klatzky and colleagues' studies (Klatzky et al., 1985, 1993; Lederman & Klatzky, 2004). In contrast, the three morphs within each of the 20 morph sets tested here all had closely related shapes. Experiment 1 investigated people's ability to name these relatively impoverished and structurally similar objects using only shape information.

Method

Participants. Twelve volunteers took part in the study. No participant in the experiments reported in this article took part in more than one study.

Materials. Three-dimensional versions of the models of the stimuli described in Lawson and Bühlhoff (2008) were printed with a Dimension three-dimensional ABS (acrylonitrile butadiene styrene) plastic printer (Dimension, Inc., Eden Prairie, MN). Twenty sets of three white plastic morphs were produced. Each set consisted of a start-point morph, a midpoint morph, and an endpoint morph, yielding 60 stimuli in total (see Figures 1 and 2). Seventeen of these morph sets were the same as those used in the sequential picture matching studies described in Lawson and Bühlhoff (2008). Some objects from the other three morph sets (canoe–rowing boat, duck–chicken, and lion–dog) could not be printed because parts of the object were too thin. These morph sets were replaced by three new sets (guitar–banjo, pencil–nail, and spray bottle–gun).

Design and procedure. On each trial the experimenter placed an object upright on the table in front of the blindfolded participant. The participant was given unlimited time to name the object and was free to rotate, pick up, and handle the object with both hands. All participants completed three blocks of 20 trials. Six participants were given the start-point morphs, then the endpoint morphs, and subsequently the midpoint morphs to identify; 6 were given the endpoint morphs, followed by the start-point morphs, then the midpoint morphs. For 3 of each of these 6 participants, each block presented the 20 morphs in a fixed order. This order was reversed for the remaining 3 participants. The experiment took between 20 and 50 min to complete.

Results

The most common name given to the start-point and endpoint morphs was usually the same for haptic and for visual presentation. Overall, 61% (standard deviation = 17%) named the start-point morphs with the most common start-point name used when the objects were presented visually (see Table 3 of Lawson & Bühlhoff, 2008), 8% gave the endpoint name, and 31% used another name (e.g., trowel for spoon, skewer for sword, or crocodile for lizard) or could not provide a name. The results were similar for the endpoint morphs: 66% (standard deviation = 15%) named them with the endpoint name, 3% gave the start-point name, and 31% gave another response. For the midpoint morphs, 30% gave the start-point name, 45% gave the endpoint name, and 25% gave another response. Thus, around two thirds of naming responses provided the same basic-level label for haptically presented objects as the most common name that was provided to pictures of these objects.

Discussion

These haptic categorization results are consistent with Klatzky et al.'s (1985, 1993) findings that the haptic recognition of familiar objects can be accurate. The results extend Klatzky et al.'s finding to impoverished models of familiar objects, which eliminated many of the cues that Klatzky et al. (1985) suggested are important for haptic identification, such as texture and size. Instead, participants were forced to use only shape information to recognize the objects. Material, texture, compliance, and temperature were identical across all of the models and usually differed markedly from the objects that they represented. No models were the correct size, with most being considerably smaller than the real object. Craddock and Lawson (in press) recently reported that there was a cost to the achievement of haptic size constancy for both real objects and the plastic models used in the present experiments. However, consistent with the successful identification of scale models in Experiment 1, this size-change cost was found to be relatively modest. Many models also represented nonrigid objects, such as animals, but all were made of the same rigid plastic. In addition, the start-point and endpoint objects from each of the 20 morph sets had similar shapes and part structures, so subtle shape information was required to accurately distinguish them. Thus, the results of Experiment 1 indicate that shape alone is sufficient to allow quite accurate haptic object recognition for structurally similar, familiar objects. Recognition of many of these objects was probably mediated by access to visual rather than haptic representations, as participants would have had little haptic experience with real versions of many of the object categories.

Haptic naming in Experiment 1 was not as good as visual recognition of two-dimensional images of these stimuli. Lawson and Bühlhoff (2008) tested the naming of pictures of 17 of these 20 morphs sets in their Experiment 4. Averaging over start-point and endpoint morphs, this study obtained an accuracy rate of 82% correct for visual naming, with 6% giving the other morph name and 12% giving another response. In contrast, haptic naming in the current Experiment 1 was 64% correct, with 6% giving the other morph name and 31% giving another response. Note that these visual and haptic results are not directly comparable, as 3 of the 20 morph sets were different and, more importantly, testing conditions were not matched. For example, unlike the visual presentations, haptic exploration was not limited to one orientation or to a fixed presentation period.

Both haptic and visual naming was less accurate for these stimuli than in most studies of object recognition. Error rates of around 5% are typical for haptically and visually presented familiar objects. This was probably because pairs of objects with highly similar shapes were tested; as responses were scored strictly, names of similar objects were scored as errors. In addition, the stimuli were models rather than real objects and thus lacked many cues (such as texture) that might normally aid recognition. Nevertheless, these results suggest that most of the stimuli presented haptically in the following experiments could have been named accurately by participants.

Experiment 2

As outlined in the introduction, researchers have reported similar patterns of brain activation, similarity ratings, cross-modal

relative to within-modal priming, and sensitivity to orientation changes for visual and haptic presentation of objects. This has led many to propose that visual and haptic inputs access common, stored, perceptual object representations. However, this hypothesis needs to be tested more rigorously (Lacey, Campbell, & Sathian, 2007). As discussed above, the results of several recent experiments have suggested that the haptic recognition of three-dimensional objects may be orientation sensitive (Craddock & Lawson, 2008; Forti & Humphreys, 2005; Lacey, Peters, & Sathian, 2007; Newell et al., 2001). However, these studies produced inconsistent results and they did not manipulate other factors which could modulate orientation sensitivity. The approach taken in the present study was to manipulate more than one variable in order to test whether the pattern of performance remains the same across both visual and haptic presentation. This prediction assumes (a) that the same perceptual representations are accessed during both haptic and visual object recognition and (b) that the factors manipulated affect performance by influencing later, object-specific processing rather than early, generic encoding stages of processing. Evidence for this second assumption is assessed in the General Discussion. There is good evidence that shape discriminability influences the sensitivity to depth rotation of visual object recognition (Lawson, 2004b; Lawson & Bühlhoff, 2008; but see Hayward & Williams, 2000). Experiment 2 therefore investigated the effects of discriminability on orientation sensitivity for haptic object recognition.

The same three-dimensional models of familiar objects used in Experiment 1 were presented in a sequential object-object matching task (see Figure 3). This experiment replicated the design of two visual matching studies, which used a computer monitor to show two-dimensional pictures depicting familiar objects (Experiment 6 of Lawson & Bühlhoff, 2008) and depicting novel, unfamiliar objects (Lawson, 2004b). Both of these earlier picture-picture matching studies explored how orientation sensitivity changed as the difficulty of shape discrimination was altered by varying the size of the shape change that occurred on mismatch trials across three groups. Within each study, the three groups differed only in the difficulty of shape discrimination required on mismatches, with all groups performing identical matches. Orientation sensitivity on matches could, therefore, be compared directly across the groups, as only the context provided by the mismatches varied across groups. In both studies, two main findings emerged (see Figures 4a and 4b). First, performance on matches was orientation sensitive even when shape changes on mismatches were always large and easy to detect. For the easy shape discrimination group, successful performance required only coarse shape discrimination, which was much easier than that required for recognizing most objects at the basic level. This result suggests that orientation sensitivity is ubiquitous in everyday visual object recognition. Second, orientation sensitivity was much greater for the hard shape-discrimination group, which had to detect small shape changes on mismatches. Orientation sensitivity was modulated by shape discriminability, with a greater same-orientation benefit when discrimination was harder and more like subordinate than basic-level visual object recognition.

Given these results, together with the evidence reviewed above of striking similarities between visual and haptic object recognition, haptic matching was predicted to be superior on same orientation as compared with orientation-change trials for all three

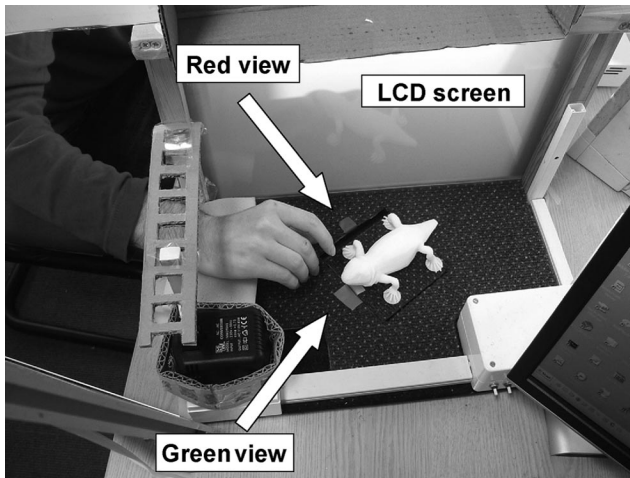


Figure 3. The experimental apparatus used in Experiments 2–5 as seen from the experimenter’s side of the apparatus. The participant’s right hand has gone through the aperture and thus has broken the infrared beam, which runs perpendicular to the glass liquid crystal display (LCD) screen beneath the ladderlike card on the left. The hand is nearly touching the object, which is the lizard start-point object from the lizard–frog morph set. The lizard is being presented at the green view, so its head is lined up with a piece of green tape on the carpet surround. The positions of the red and green views are indicated by arrows. The lizard would need to be rotated by 90° clockwise to be presented at the red view. The LCD screen is clouded, so the participant cannot see the lizard through it. The LCD screen was cleared when the participant had visual inputs.

groups tested in Experiment 2. Second, this orientation sensitivity was expected to be greater when shape discrimination was harder, mirroring the pattern of performance previously observed for visual object recognition (Lawson, 2004b; Lawson & Bühlhoff, 2008).

Method

Participants. There were 48 participants. In this and the subsequent studies, participants were right-handed undergraduate students from the University of Liverpool, United Kingdom, who took part in the study for course credit. Their ages ranged from 18 to 47 years, with most being between 18 and 19 years. In Experiments 2, 3, 4, and 5, there were 1, 0, 2, and 2 participants, respectively who were older than 30 years of age.

Materials and apparatus. The 20 sets of three morphs presented in Experiment 1 were used. Each morph was glued upright onto a 10-cm square base made of carpet tile (see Figure 2). 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 square hole cut into a surround made out of a carpet tile (see Figures 3, 5, and 6). 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 orientations, respectively, so there was a 90° depth rotation on orientation-change trials.

It is important to clarify what was meant by haptic orientation in the present set of experiments. Both visual and haptic object

orientation were specified with respect to the trunk of the participant. This, in turn, was fixed with respect to the environment: the experimental testing room. Thus the influence of these two reference frames, body-centered and environmental context, were confounded. Participants were free to move their head, and they could feel around all sides of an object. This ability to alter the orientation of their sensors (eyes, hand, and fingers) may have reduced the orientation effects reported here. However, any such changes were probably small relative to the 90° depth rotations that were used in the present studies. For example, in the present studies (as in most everyday situations), objects could not be felt equally effectively from all sides. First, there are biomechanical limits on the extent to which the fingers and thumb can move independently and the range of relative positions of the hand, arm, and body. Second, the participant’s hand entered the apparatus through a narrow aperture (12 × 12 cm; see Figure 3), further restricting movement. Furthermore, although it is often assumed that visual object orientation is defined with respect to retinal coordinates, Waszak, Drewing, and Mausfeld (2005) found that gravity and global room context can both serve to define the reference frame used in visual object processing, and these contexts were fixed during the experiment. There is no reason to assume that eye or hand–finger position wholly determines perceived visual and haptic orientation, respectively. Instead, it is likely that a weighted combination of multiple reference frames is used (Volcic, Kappers & Koenderink, 2007). Investigating what determines which reference frames are involved when three-dimensional objects are identified visually and haptically will be an important area for future study.

The object was hidden from the participant’s view by card, a board, and a clouded liquid crystal display (LCD) glass screen produced by SmartGlass International (Hampshire, United Kingdom), which was 36 cm wide × 29 cm high (see Figures 3 and 6). Behind and perpendicular to this glass screen was a 12-cm square aperture through which the participant’s right hand entered in order to touch the object. An infrared beam shone across this aperture, placed so that it was broken when the participant’s hand entered the aperture. When this beam was broken, a detector sent a signal to the computer controlling the experiment. Participants responded using a button box, which was placed on the table next to their left hand, in front of the glass screen.

Design and procedure. All participants completed one block of 80 trials comprising four subblocks of 20 trials. A start-point or endpoint morph from each of the 20 sets was presented once as the first object in each subblock. 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 in depth and the other trial presenting the second object rotated in depth by 90° relative to the first. Both mismatch trials presented the same distractor as the second object.

One group of 10 morph sets was presented on 40 of the trials in a block. On these trials, the first object presented was the start-point morph. On matches, the second object presented was the same start-point morph. On mismatches, the second object presented was the midpoint morph from the same morph set, the endpoint morph from the same morph set, or the start-point morph from a different morph set for the hard, medium, and easy shape discrimination groups, respectively. Similar conditions were run

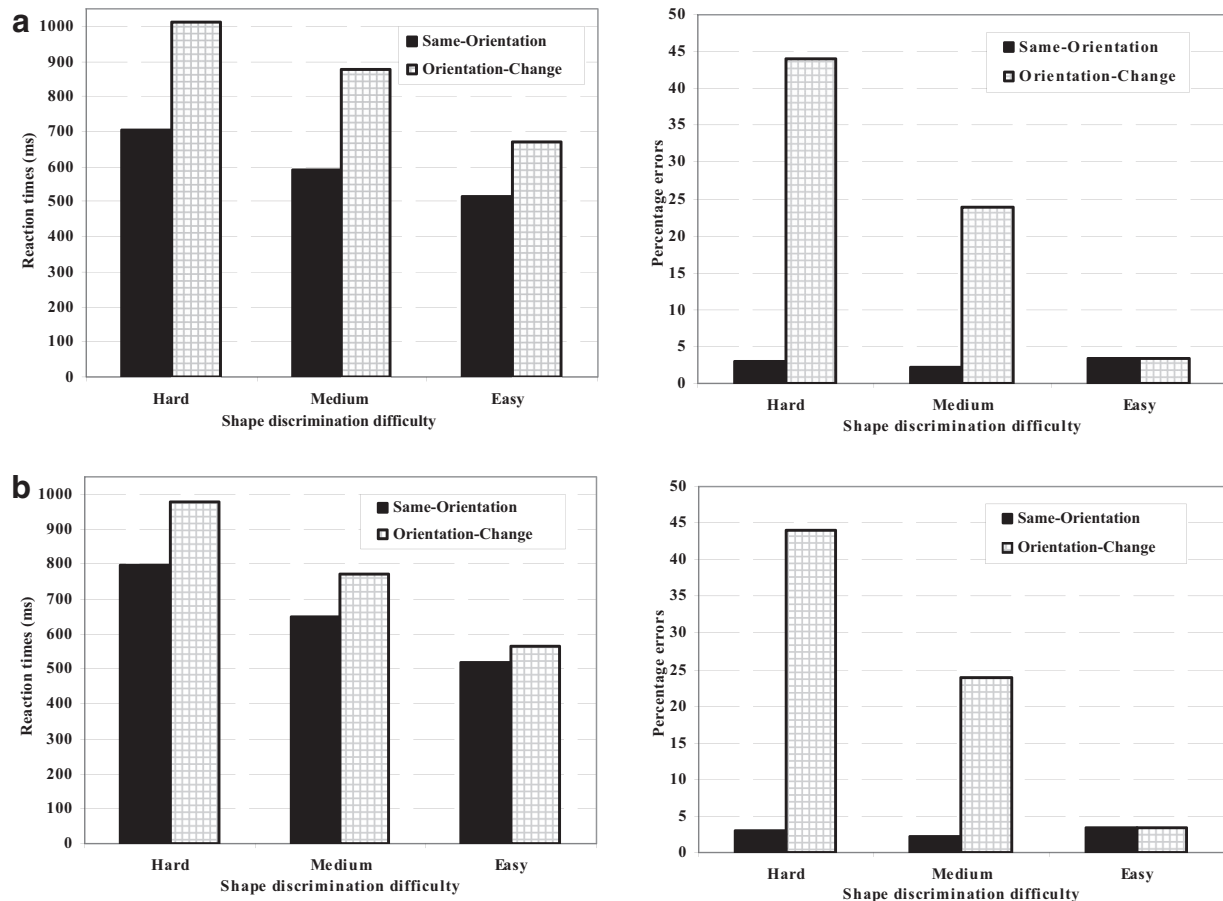


Figure 4. Mean correct reaction times (on the left) and mean percentage errors (on the right) for four within-modal, sequential matching studies, each with the same overall design: (a) results from Lawson (2004b) for visual–visual matching of two-dimensional pictures of novel objects; (b) results from Experiment 6 of Lawson and Bühlhoff (2008) for visual–visual matching of two-dimensional pictures of familiar objects; (c) results from Experiment 3 here for visual–visual matching of three-dimensional familiar objects; (d) results from Experiment 2 here for haptic–haptic (HH) matching of three-dimensional familiar objects. Results are shown for match trials only, for same-orientation and orientation-change trials separately, for the hard, medium, and easy shape discrimination groups. Within each study, match trials were identical across all groups, with only the difficulty of mismatches differing between the groups. For the results of the two earlier studies (a and b), the orientation-change means are the average of results for 30° and 150° depth rotations. For the results of the two studies reported here (c and d), the orientation-change results are for 90° depth rotations.

for the second group of 10 morph sets, which were presented on the remaining 40 trials. However, on these trials, the first object presented was the endpoint morph. On matches, the second object presented was the same endpoint morph. On mismatches, the second object presented was the midpoint morph from the same morph set, the start-point morph from the same morph set, or the endpoint morph from a different morph set for the hard, medium, and easy shape discrimination groups, respectively.

Sixteen participants were assigned to each mismatch shape change group. Only the mismatches differed across these three groups. Within each group, the assignment of morph set subgroup to the first morph (whether start point or endpoint) was counter-balanced across two subgroups of 8 participants. For 4 of these 8 people, if the first object on a trial was a morph from the first subgroup, it was presented from the red orientation; if it was a

morph 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. For each of these 4 people, 2 were given trials from the 20 morph sets in one fixed order within each subblock (with the bottle-watering can morph set presented on the first trial), and the other 2 were given the same trials in the reverse order (with the bottle-watering can morphs presented on the last trial).

The experiment was run on a computer with E-Prime Version 1.1 experimental presentation software (Psychology Software Tools, Inc., Pittsburgh, PA). At the start of each trial, the experimenter placed the first object behind the screen, then triggered the computer to play the words “go now”: This signaled to the participant that they could start to move his or her right hand through the aperture to touch the object behind the screen. The computer

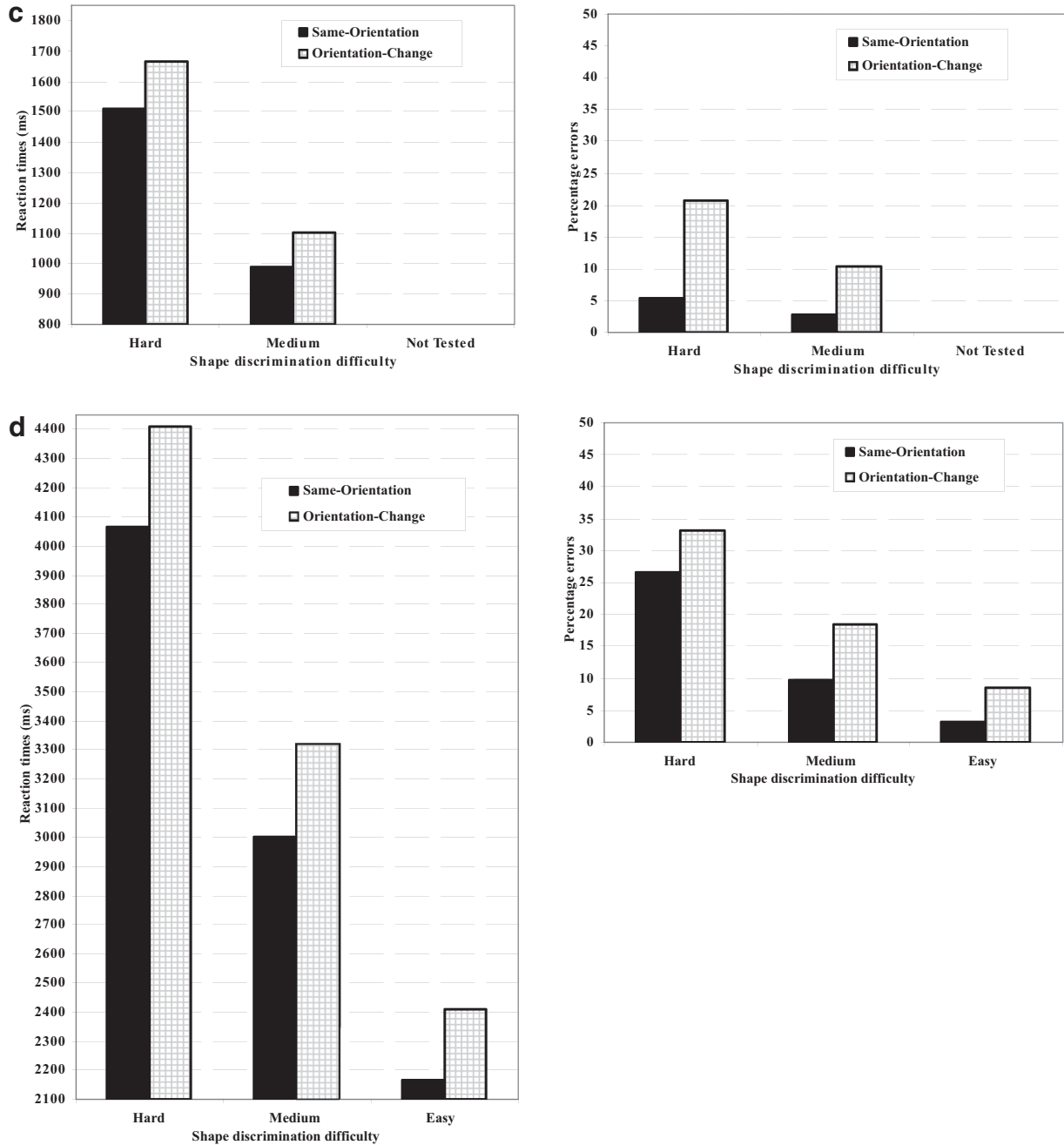


Figure 4 (continued).

recorded the time at which the hand broke the infrared beam across the aperture. Five seconds after the beam was broken, the words “stop now” were played by the computer, signaling 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 his or her hand back through the aperture to touch the second object.

The participant then decided whether the two successively presented objects had the same shape and responded with a speeded key press. The computer recorded the time from when the participant’s right hand broke the infrared beam until he or she responded with the left hand by pressing one of two buttons (marked “same” and “different”) on a response button box. The participant was told to ignore any difference in the orientation of the first and second objects. The participant was also warned that on mismatches, the two objects might have very similar shapes. After responding, the participant heard either a high or a low double tone

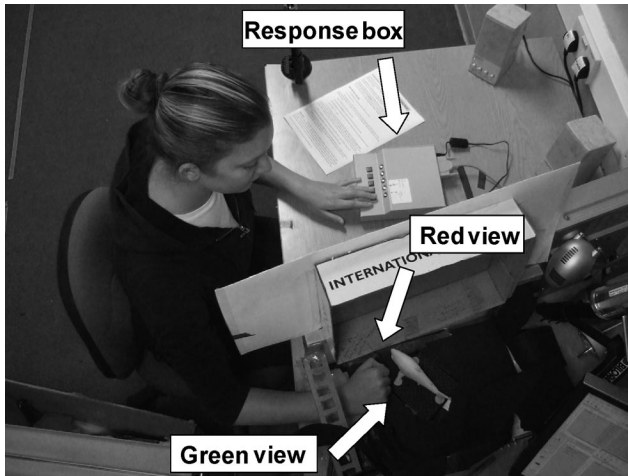


Figure 5. The experimental apparatus used in Experiments 2–5 as seen from above. The participant’s right hand has gone through the aperture and so has broken the infrared beam, which runs under the ladderlike card on the left. The fish start-point object from the fish–shark morph set is being presented at the red view, so its head points towards the participant’s head and body. If it were positioned at the green view, it would be rotated counterclockwise by 90° and its head would point to the right of the participant’s head and body. The participant’s left hand is placed ready to respond using the response button box.

as feedback, which indicated a correct or an incorrect response, respectively. Participants completed a block of 10 practice trials prior to starting the experimental block. These trials were identical to the final 10 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 haptic 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 the participant could not determine from the movements of the experimenter whether he or she was going to be given a match or a mismatch trial. At the end of the study, each participant was asked whether he or she had used only information obtained by touch to make a response or whether the participant had also used auditory or visual information, such as the sounds of the experimenter moving objects or seeing the objects. All participants said that they had used only information obtained by touch.

Results

Analyses of variance (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 responses were correct. Response latencies of less than 750 ms or those exceeding 10,000 ms were discarded as errors (fewer than 1% of trials). No participants were replaced. There was one empty cell in

the by-items analysis for the medium discrimination group, which was replaced by the mean for that condition.

There was one within-participant variable, orientation change (0° or 90°), and one between-participants variable, shape discrimination (easy, medium, or hard group). There were also two counterbalancing factors: the within-participant variable of morph set subgroup (whether the first object on a trial was the start-point 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 variable 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 this or subsequent experiments. All pairwise differences noted below were significant ($p < .05$) in by-participants and by-items post hoc Newman-Keuls analyses. The results for the F values in the by-participants and by-items analyses are reported as F_1 and F_2 , respectively.

Same-shape matches. Orientation change was significant for both RTs, $F_1(1, 42) = 44.07$, $p < .001$, partial $\eta^2 = 0.51$, $F_2(1, 18) = 39.12$, $p < .001$, partial $\eta^2 = 0.69$, and errors, $F_1(1, 42) = 14.52$, $p < .001$, partial $\eta^2 = 0.26$, $F_2(1, 18) = 11.87$, $p < .004$, partial $\eta^2 = 0.40$. Same-orientation matches (3,078 ms, 13% errors) were 302 ms faster and 7% more accurate than 90° orientation-change matches (3,380 ms, 20%).

Shape discriminability was significant for both RTs, $F_1(2, 42) = 33.52$, $p < .001$, partial $\eta^2 = 0.62$, $F_2(2, 36) = 520.91$, $p < .001$, partial $\eta^2 = 0.97$, and errors, $F_1(2, 42) = 51.748$, $p < .001$, partial $\eta^2 = 0.71$, $F_2(2, 36) = 66.80$, $p < .001$, partial $\eta^2 = 0.79$. The easy discrimination group (2,288 ms, 6% errors), who only had to detect large shape changes on mismatches, were 871 ms faster and 6% more accurate than the medium discrimination group (3,159 ms, 14%) who, in turn,

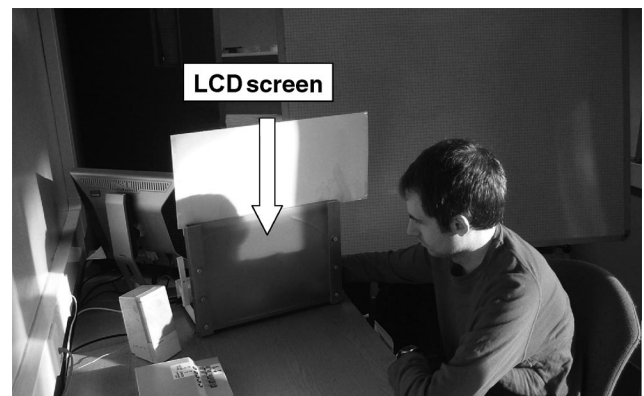


Figure 6. The experimental apparatus used in Experiments 2–5 as seen from the participant’s side of the apparatus. The participant’s right hand has gone through the aperture in order to touch an object, and the glass liquid crystal display (LCD) screen is clouded so that the participant cannot see through it. A card was placed above the screen and there was a board next to the participant to block his or her view to ensure that the participant could not see the objects on the shelves or as they were placed into the apparatus. The glass LCD screen was cleared when the participant had visual inputs.

were 1,080 ms faster and 16% more accurate than the hard discrimination group (4,239 ms, 30%), who had to detect small, subtle shape changes on mismatches. Note that these large differences among the three groups were due solely to the mismatch context, as these results were for match trials, which were identical across all three groups.

Most importantly, and in contrast to the results for studies using the same paradigm but presenting two-dimensional pictures of objects in a visual matching task (Lawson, 2004b; Lawson & Bühlhoff, 2008), the Orientation Change \times Shape Discriminability interaction was not significant for either RTs, $F_1(2, 42) = 0.47$, $p > .60$, partial $\eta^2 = 0.02$, $F_2(2, 36) = 1.52$, $p > .20$, partial $\eta^2 = 0.08$, or for errors, $F_1(2, 42) = 0.31$, $p > .70$, partial $\eta^2 = 0.02$, $F_2(2, 36) = 0.30$, $p > .70$, partial $\eta^2 = 0.02$ (see Figure 4d). Orientation sensitivity was similar for all three groups despite large overall differences in their performance levels. For the easy discrimination group, same-orientation matches were 240 ms faster and 5% more accurate than orientation-change matches. For the medium discrimination group, same-orientation matches were 320 ms faster and 9% more accurate. For the hard discrimination group, same-orientation matches were 344 ms faster and 7% more accurate.

Shape-change mismatches. Mismatches were not the focus of this study, as, unlike matches, different stimuli were presented to the three groups on these trials. Nevertheless, for completeness, the results are reported in brief. Orientation change was significant for RTs, $F_1(1, 42) = 5.94$, $p < .02$, $F_2(1, 18) = 8.75$, $p < .009$, but not for errors, $F_1(1, 42) = 0.27$, $p > .60$, $F_2(1, 18) = 0.48$, $p > .40$. Same-orientation mismatches (2,888 ms, 19% errors) were faster than 90° orientation-change mismatches (3,031 ms, 18% errors). Shape discriminability was significant for both RTs $F_1(2, 42) = 28.64$, $p < .001$, $F_2(2, 36) = 146.51$, $p < .001$, and errors, $F_1(2, 42) = 78.48$, $p < .001$, $F_2(2, 36) = 37.29$, $p < .001$. The easy discrimination group (1,925 ms, 3% errors) responded much faster and more accurately than the medium discrimination group (3,103 ms, 18%), who, in turn, responded much faster and more accurately than the hard discrimination group (3,851 ms, 34%). The Orientation Change \times Shape Discriminability interaction was not significant for either RTs, $F_1(2, 42) = 1.82$, $p > .10$, $F_2(2, 36) = 2.58$, $p > .08$, or errors, $F_1(2, 42) = 0.19$, $p > .80$, $F_2(2, 36) = 0.22$, $p > .80$. The nearly significant interaction for RTs was due to greater orientation sensitivity for the hard discrimination group (252 ms, same orientation advantage) and the medium discrimination group (189 ms) in comparison with the easy discrimination group (-11 ms). The lack of orientation effect for the easy discrimination condition is unsurprising, as two objects with unrelated shapes were presented on easy mismatch trials (e.g., bench, then bottle). It is almost meaningless to try to specify orientation changes across such object pairs (Lawson & Bühlhoff, 2006).

Discussion

First, orientation sensitivity was found for all three groups in Experiment 2. Matching was both faster and more accurate when an object was presented from the same orientation twice than when it was rotated by 90° in depth from the first to the second time that it was presented on a trial. This is consistent with recent reports that haptic object recognition is orientation sensitive (Craddock &

Lawson, 2008; Forti & Humphreys, 2005; Lacey, Peters, & Sathian, 2007; Newell et al., 2001), and it extends this result to a new task and a different type of stimuli.

Second, shape discriminability had a powerful effect on haptic matching. The easy discrimination group, which only had large shape changes to detect, were much faster and more accurate than the hard discrimination group, which always had small shape changes to detect.

Third, although shape discriminability and orientation changes each had substantial individual effects on haptic matching, there was no interaction between them. The additive effects of these two factors contrast with the strong interaction between shape discriminability and orientation sensitivity that has been found in previous visual matching studies in which two-dimensional pictures of three-dimensional objects were presented (Lawson, 2004b; Lawson & Bühlhoff, 2008). In these picture–picture matching studies, orientation sensitivity was much greater when shape change detection was more challenging: It was increased for the medium and, especially, the hard discrimination groups relative to the easy discrimination groups (see Figures 4a and 4b).

Experiment 3

There was a clear difference between the results of Experiment 2, which presented three-dimensional objects in a haptic object matching task, and a study with a similar design that presented two-dimensional pictures of most of the same objects in a visual object matching task (Lawson & Bühlhoff, 2008, see Figure 4b; see also Lawson, 2004b, see Figure 4a). However, for technical reasons, there were a number of potentially important differences between the haptic and the visual studies. For example, stimulus presentation was slower in Experiment 2 because people typically take longer to acquire information about the shape of objects haptically compared with visually (e.g., Lacey & Campbell, 2006). In Experiment 2, people were given 5 s to haptically explore the first object, and the interstimulus interval was around 2 s, whereas in the visual matching study, the first picture was shown for just 500 ms, with an interstimulus interval of only 400 ms. Orientation sensitivity has been found to diminish as the interstimulus interval increases (e.g., Ellis & Allport, 1986; Lawson & Humphreys, 1996), so this difference might have reduced overall effects of depth rotation in Experiment 2. In addition, three-dimensional objects were presented in Experiment 2, whereas two-dimensional pictures of three-dimensional objects were shown on a computer monitor in the visual matching study. Orientation sensitivity may be weaker for stimuli with more depth cues (Bennett & Vuong, 2006; Burke, 2005; Humphrey & Khan, 1992), so again, this difference might have reduced any effects of depth rotation in Experiment 2. There were numerous other differences between the two studies. The size of the orientation change was 90° in Experiment 2, but it was either 30° or 150° in the visual study. Responses were made unimanually with a button box in Experiment 2, but bimanually with a computer keyboard in the visual study. People self-triggered response timing in Experiment 2 but not in the visual study. One or more of these differences, rather than the change of input modality from vision to haptics, may have been the reason why the results of Experiment 2 did not replicate the interaction between orientation sensitivity and shape discriminability reported in Lawson and Bühlhoff (2008).

To test this possibility, Experiment 3 replicated Experiment 2 but involved a visual matching task. The same three-dimensional plastic stimuli were used in the same apparatus, with the same cues and feedback as in Experiment 2. The first object was visible through the LCD screen for 4.5 s, followed by a blank interstimulus interval of about 2 s while the first object was replaced by the second object, so the timing of stimulus exposures was similar across the two studies. People moved their hand into the aperture behind the screen to break an infrared beam, which caused the LCD screen to clear so that they could see objects through it. Their body position, initial hand movements, and the object orientations tested were thus the same as in Experiment 2 and, as in that study, people responded using a button box with their left hand.

Given the previous results with two-dimensional pictures of these three-dimensional objects (Lawson & Bühlhoff, 2008), an interaction between the effects of orientation change and shape discriminability was predicted in Experiment 3, with greater orientation sensitivity expected when shape discrimination was harder. Because the extended presentation time of the first object was expected to make this visual matching task easy, only the medium and hard discrimination groups were tested. Overall performance of the hard and medium unimodal VV groups was expected to be similar to that of the medium and easy unimodal HH groups tested in Experiment 2.

Method

Participants. A total of 32 right-handed participants took part in this experiment.

Materials and apparatus. The materials and apparatus were identical to those used in Experiment 2 except that an extra piece of card was placed behind the LCD screen. This card prevented people from moving their hand fully through the aperture so that they could not touch the object, and it also hid their right hand from view through the screen.

Design and procedure. The design and procedure were identical to Experiment 2 except for the following points. Only two groups (the medium and hard mismatch shape change groups) were tested. After an object had been placed and participants heard “go now,” they moved their hand through the aperture to break the infrared beam, as in Experiment 2. However, in contrast to Experiment 2, they were prevented from touching the object by a piece of card. Instead, the LCD glass screen cleared 500 ms after the beam was broken, enabling the participants to see the object. For the first object on a trial, the screen clouded 4,500 ms after it had cleared. After another 500 ms, the words “stop now” were played by the computer. For the second object on a trial, the screen clouded immediately after the participant had responded.

Results

ANOVAs were conducted on the mean correct RTs and on the percentage of errors for matches and mismatches separately. On matches, same-shape responses were correct, whereas on mismatches, shape-change responses were correct. Response latencies of less than 375 ms or exceeding 5,000 ms were discarded as errors (fewer than 1% of trials). No participants were replaced, and there were no empty cells. The same analyses were conducted as in Experiment 2 except that there were only two shape discrimination

groups (medium and hard). All pairwise differences noted below were significant ($p < .05$) in by-participants and by-items post hoc Newman-Keuls analyses.

Same-shape matches. Orientation change was significant for both RTs, $F_1(1, 28) = 12.12, p < .003$, partial $\eta^2 = 0.30$, $F_2(1, 18) = 13.61, p < .003$, partial $\eta^2 = 0.43$, and errors, $F_1(1, 28) = 41.13, p < .001$, partial $\eta^2 = 0.60$, $F_2(1, 18) = 63.02, p < .001$, partial $\eta^2 = 0.78$. Same-orientation matches (1,250 ms, 4% errors) were 135 ms faster and 11% more accurate than 90° orientation-change matches (1,385 ms, 15% errors).

Shape discriminability was significant for both RTs, $F_1(1, 28) = 15.24, p < .002$, partial $\eta^2 = 0.35$, $F_2(1, 18) = 267.93, p < .001$, partial $\eta^2 = 0.94$, and errors, $F_1(1, 28) = 13.27, p < .001$, partial $\eta^2 = 0.32$, $F_2(1, 18) = 14.88, p < .001$, partial $\eta^2 = 0.45$. The medium discrimination group (1,047 ms, 7% errors) was 541 ms faster and 6% more accurate than the hard discrimination group (1,588 ms, 13% errors), which had to detect smaller shape changes on mismatches. Note that the substantial differences between these two groups were due solely to the mismatch context, as these results were for matches that were identical across both groups.

Most importantly, these two main effects interacted. The Orientation Change \times Shape Discriminability interaction was not significant for RTs, $F_1(1, 28) = 0.32, p > .50$, partial $\eta^2 = 0.01$, $F_2(1, 18) = 0.79, p > .30$, partial $\eta^2 = 0.04$, but was significant for errors, $F_1(1, 28) = 4.82, p < .04$, partial $\eta^2 = 0.15$, $F_2(1, 18) = 8.31, p < .02$, partial $\eta^2 = 0.32$ (see Figure 4c). Accuracy was more orientation sensitive for the hard discrimination group. Here, same-orientation matches were 157 ms faster and 15% more accurate than orientation-change matches. For the medium discrimination group, same-orientation matches were 113 ms faster and 8% more accurate than orientation-change matches. This finding of a greater same-orientation benefit when shape discrimination is harder replicates that found for visual matching tasks presenting two-dimensional pictures of morphs reported by Lawson (2004b; see Figure 4a) and Lawson and Bühlhoff (2008; see Figure 4b). However, it contrasts with the additive effects of orientation change and shape discriminability found for the haptic matching task tested in Experiment 2 (see Figure 4d).

Shape-change mismatches. Mismatches were not the focus of this study, as, unlike matches, different stimuli were presented to the two groups on these trials. Nevertheless, for completeness, the results are reported in brief. Orientation change was not significant for RTs, $F_1(1, 28) = 2.84, p > .10$, $F_2(1, 18) = 2.27, p > .10$, or errors, $F_1(1, 28) = 0.80, p > .30$, $F_2(1, 18) = 0.80, p > .30$, with similar performance for same-orientation mismatches (1,156 ms, 7% errors) and 90° orientation-change mismatches (1,197 ms, 8% errors). Shape discriminability was significant for both RTs, $F_1(1, 28) = 6.85, p < .02$, $F_2(1, 18) = 108.37, p < .001$, and errors, $F_1(1, 28) = 20.23, p < .04$, $F_2(1, 18) = 11.23, p < .005$. The medium discrimination group (1,006 ms, 4% errors) responded much faster and more accurately than did the hard discrimination group (1,347 ms, 11% errors). Finally the Orientation Change \times Shape Discriminability interaction was not significant for either RTs, $F_1(1, 28) = 3.70, p > .06$, $F_2(1, 18) = 2.24, p > .10$, or errors, $F_1(1, 28) = 1.25, p > .2$, $F_2(1, 18) = 0.88, p > .30$.

Discussion

As in Experiment 2, both orientation changes and shape discriminability had powerful effects on performance in Experiment 3. People were much faster and more accurate on same-orientation trials than on orientation-change trials and also when they had to detect only relatively large shape changes, for the medium as compared with the hard discrimination group. Most importantly, and in contrast to Experiment 2, there was also an interaction between the effects of these two variables. Orientation sensitivity was greater for the hard than for the medium discrimination group, replicating the pattern of results found for the same task presenting two-dimensional pictures of three-dimensional objects on a computer monitor (Lawson, 2004b; Lawson & Bühlhoff, 2008). However, orientation sensitivity was weaker overall in Experiment 3 compared with results in these previous studies (see Figure 4). The differing influence of shape discriminability on orientation sensitivity across Experiments 2 and 3 provides evidence against the hypothesis that haptic and visual inputs access common, stored perceptual representations of objects. This hypothesis was tested further by investigating cross-modal matching in Experiments 4 and 5.

There are a number of possible reasons for the reduced main effect of orientation changes in Experiment 3. One likely cause was the increased interstimulus interval of approximately 2 s in Experiment 3 as compared with 400 ms in the earlier studies. Orientation sensitivity for visual object recognition has been found to dissipate over time. For example, Lawson and Humphreys (1996; see also Ellis & Allport, 1986) reported greater orientation sensitivity in a picture–picture matching task after a 600-ms interstimulus interval than after a 2,500-ms interstimulus interval. This, in turn, may be because people are more likely to rely on an orientation-invariant verbal strategy of remembering the name of the first object presented during the interstimulus interval if it lasts several seconds. Alternatively, different frames of reference may dominate performance at longer interstimulus intervals (Zuidhoek, Kappers, van der Lubbe, & Postma, 2003).

Another reason for the weaker orientation sensitivity in Experiment 3 could be the fact that three-dimensional objects were presented. These objects provided stereoscopic information about depth, which was absent from two-dimensional pictures of the same objects. Object constancy over depth rotation has been found to be achieved more efficiently when useful stereoscopic information is available (Bennett & Vuong, 2006; Burke, 2005; Humphrey & Khan, 1992).

A third reason for the reduced orientation sensitivity might be that people in Experiment 3 could alter their view of an object by moving their head, and therefore the orientation of the object was not as strictly controlled as when two-dimensional pictures of three-dimensional objects shown from a fixed orientation are presented on a computer monitor. Object orientation in Experiment 3 was more similar to that for haptic presentation in Experiment 2, in which the hand was not restricted to touching one surface of the object.

Although orientation sensitivity for visual matching was reduced in Experiment 3, it is important to emphasize that it still interacted significantly with shape discriminability. This suggests that the additive effects of orientation change and shape discriminability found for HH matching in Experiment 2 were due to the

modality of presentation and not merely to changes in the experimental procedure. However, this conclusion must be tempered by the observation that the interaction for VV matching in Experiment 3 was not as striking as for the previous two-dimensional VV matching studies (Lawson, 2004b; Lawson & Bühlhoff, 2008).

A final caveat to the interpretation of these results is that the two orientations tested in Experiments 2 and 3 cannot be assumed to be equivalent across the visual and haptic input modalities. In all of the present experiments, orientation was defined relative to the trunk of the observer. However, the angle of the object relative to the right hand (in Experiment 2) and the eye (in Experiment 3) were different, and this might have influenced the results. Yet, data from an unpublished study that replicated Experiment 2 but with a within-participant manipulation of shape discriminability provided evidence that the choice of orientations tested here was not critical. This study tested a different pair of orientations: the green orientation and an orientation rotated 90° counterclockwise. This second orientation was therefore rotated 180° from the red orientation used in the present experiments. Here, orientation changes produced a similar cost for haptic–haptic matching as was found in Experiment 2. More generally, it is not possible to fully equate the effects of object orientation across visual and haptic inputs given the profound differences in how visual and haptic information is acquired and the nonveridical perception of space across both modalities (Volcic et al., 2007; Zuidhoek, Visser, Bredero, & Postma, 2004). However, it is important to note that in all of the present experiments, the orientation-change condition involved the same, large (90°) depth rotation and that the main cross-study comparison was not the absolute magnitude of orientation effects but the interaction of these effects with shape discriminability.

Experiment 4

The effect of manipulating shape discriminability on orientation sensitivity differed across within-modal HH versus VV matching in Experiments 2 and 3, respectively. This suggests that orientation sensitivity may not have the same cause in the two modalities. As a further test of this hypothesis, cross-modal VH and HV matching was investigated in Experiments 4 and 5, respectively. The evidence reviewed in the introduction indicates that access to stored, orientation-sensitive representations causes visual orientation sensitivity. If the same stored perceptual representations are accessed by both visual and haptic inputs, then similar orientation effects should occur for cross-modal as for within-modal matching. However, if orientation sensitivity has a different cause for haptic versus visual object recognition, which is the preliminary conclusion based on the results of Experiments 2 and 3, then orientation sensitivity might differ for within-modal and cross-modal matching and for VH versus HV cross-modal matching.

It is difficult to make predictions about the orientation sensitivity of cross-modal object recognition from the mixed evidence available to date. As discussed in the introduction, orientation sensitivity was reported for both VH and HV matching by Newell et al. (2001). In contrast, using a similar task and stimuli to Newell et al., Lacey, Peters, and Sathian (2007) reported orientation-invariant VH and HV matching. The main difference between these two studies was that Lacey et al. presented objects at an oblique angle rather than directly facing the participant's trunk and hand. Finally, Forti and Humphreys (2005) reported a patient with

a same-orientation benefit for HV matching (VH matching was not tested). Note that this latter result reveals a pattern of orientation sensitivity opposite to that reported by Newell et al. (2001), who found superior old–new recognition when there was a study–test change of orientation (from a haptic front to a visual rear orientation or vice versa) relative to same-orientation conditions. Newell et al.'s result, however, may be an artifact due to biomechanical constraints (Lacey, Peters, & Sathian, 2007). If so, this still leaves open the question of whether cross-modal object recognition is orientation sensitive (Forti & Humphreys, 2005; but see Lacey, Peters, & Sathian, 2007) and whether any orientation sensitivity differs for VH and HV matching.

Experiment 4 tested VH matching using the same sequential matching task and the same stimuli and apparatus as in Experiments 2 and 3. The first object was presented visually, and the second object was presented haptically. As in Experiment 3, two groups were tested, one with a hard shape discriminability task and the other with one of medium difficulty.

Method

Participants. A total of 32 participants took part in this experiment; all but 1 (in the medium discrimination condition) were right-handed.

Materials and apparatus. The materials and apparatus were identical to those used in Experiment 2.

Design and procedure. The design and procedure used in this experiment were identical to those used in Experiment 3 except that participants saw the first object (so the first part of the trial was identical to Experiment 3) and then felt the second object (so the second part of the trial was identical to Experiment 2). Among the participants, 16 were assigned to the hard mismatch shape change group, and 16 were assigned to the medium mismatch shape change group.

Results

ANOVAs were conducted on the mean correct RTs and on the percentage of errors for matches and mismatches separately. On matches, same-shape responses were correct, whereas on mismatches, shape-change responses were correct. As in Experiment 2, response latencies of less than 750 ms or exceeding 10,000 ms were discarded as errors (fewer than 1% of trials). No participants were replaced. There were three empty cells in the by-items analysis for the hard discrimination group, which were replaced by the means for those conditions.

Same-shape matches. Orientation change was significant for both RTs, $F_1(1, 28) = 18.66, p < .001$, partial $\eta^2 = 0.40$, $F_2(1, 18) = 24.85, p < .001$, partial $\eta^2 = 0.58$, and for errors, $F_1(1, 28) = 4.63, p < .05$, partial $\eta^2 = 0.14$, $F_2(1, 18) = 8.06, p < .02$, partial $\eta^2 = 0.31$. Same-orientation matches (3,582 ms, 12% errors) were 291 ms faster and 4% more accurate than 90° orientation-change matches (3,873 ms, 16% errors).

Shape discriminability was also significant for both RTs, $F_1(1, 28) = 4.54, p < .05$, partial $\eta^2 = 0.14$, $F_2(1, 18) = 219.25, p < .001$, partial $\eta^2 = 0.92$, and errors, $F_1(1, 28) = 12.51, p < .002$, partial $\eta^2 = 0.31$, $F_2(1, 18) = 19.90, p < .001$, partial $\eta^2 = 0.53$. The medium discrimination group (3,282 ms, 10%) was 891 ms faster and 9% more accurate than the hard discrimination group

(4,173 ms, 19%), who had to detect smaller shape changes on mismatches. Note that the substantial differences between these two groups were due solely to the mismatch context, as these results were for matches that were identical across both groups.

Most importantly, these two main effects did not interact. The Orientation Change \times Shape Discriminability interaction was not significant for either RTs, $F_1(1, 28) = 2.09, p > .10$, partial $\eta^2 = 0.07$, $F_2(1, 18) = 0.91, p > .30$, partial $\eta^2 = 0.05$, or for errors, $F_1(1, 28) = 0.59, p > .40$, partial $\eta^2 = 0.02$, $F_2(1, 18) = 0.83, p > .30$, partial $\eta^2 = 0.04$ (see Figure 7a). The same-orientation benefit was nonsignificantly smaller on RTs and nonsignificantly larger on errors for the medium discrimination group (193 ms, 6% for errors) compared with the hard discrimination group (388 ms, 3%). The overall cost for achieving object constancy was about the same irrespective of shape discriminability.

Shape-change mismatches. Mismatches were not the focus of this study, as, unlike matches, different stimuli were presented to the two groups on these trials. Nevertheless, for completeness, the results are reported in brief. Orientation change was not significant for either RTs, $F_1(1, 28) = 2.18, p > .10$, $F_2(1, 18) = 0.46, p > .50$, or for errors, $F_1(1, 28) = 0.04, p > .80$, $F_2(1, 18) = 0.05, p > .80$. Responses were similar to same-orientation matches (3,412 ms, 33% errors) and 90° orientation-change matches (3,546 ms, 32%). Shape discriminability was significant for both RTs, $F_1(1, 28) = 6.38, p < .02$, $F_2(1, 18) = 77.49, p < .001$, and for errors, $F_1(1, 28) = 82.70, p < .001$, $F_2(1, 18) = 104.23, p < .001$. The medium discrimination group (3,026 ms, 19%) was 905 ms faster and 27% more accurate than the hard discrimination group (3,931 ms, 46%). The Orientation Change \times Shape Discriminability interaction was not significant for either RTs, $F_1(1, 28) = 1.09, p > .30$, $F_2(1, 18) = 0.60, p > .40$, or for errors, $F_1(1, 28) = 2.29, p > .10$, $F_2(1, 18) = 2.09, p > .10$.

Discussion

Contrary to both the orientation-invariant VH matching reported by Lacey, Peters, and Sathian (2007) and the orientation-change benefit for VH matching reported by Newell et al. (2001), Experiment 4 revealed superior same orientation, as compared with orientation-change performance, for VH matching. Furthermore the pattern of results replicated Experiment 2 for HH matching in that the cost of an orientation change on performance was similar irrespective of the difficulty of shape discrimination (see Figure 4d). This contrasts with the interaction between the effects of orientation change and shape discriminability found for VV matching of the same three-dimensional objects (in Experiment 3 here, see Figure 4c; see also Figure 4a of Lawson, 2004b, and Figure 4b of Lawson & Bühlhoff, 2008). This finding is discussed further in the General Discussion, following presentation of the results from the HV matching task in the next section.

Experiment 5

Experiment 5 investigated the orientation sensitivity of HV matching and thus complemented Experiment 4, which tested VH matching. Neither of the studies that have tested the orientation sensitivity of HV and VH matching (Lacey, Peters, & Sathian, 2007; Newell et al., 2001) found a difference between these two cross-modal conditions. However, because the pattern of orienta-

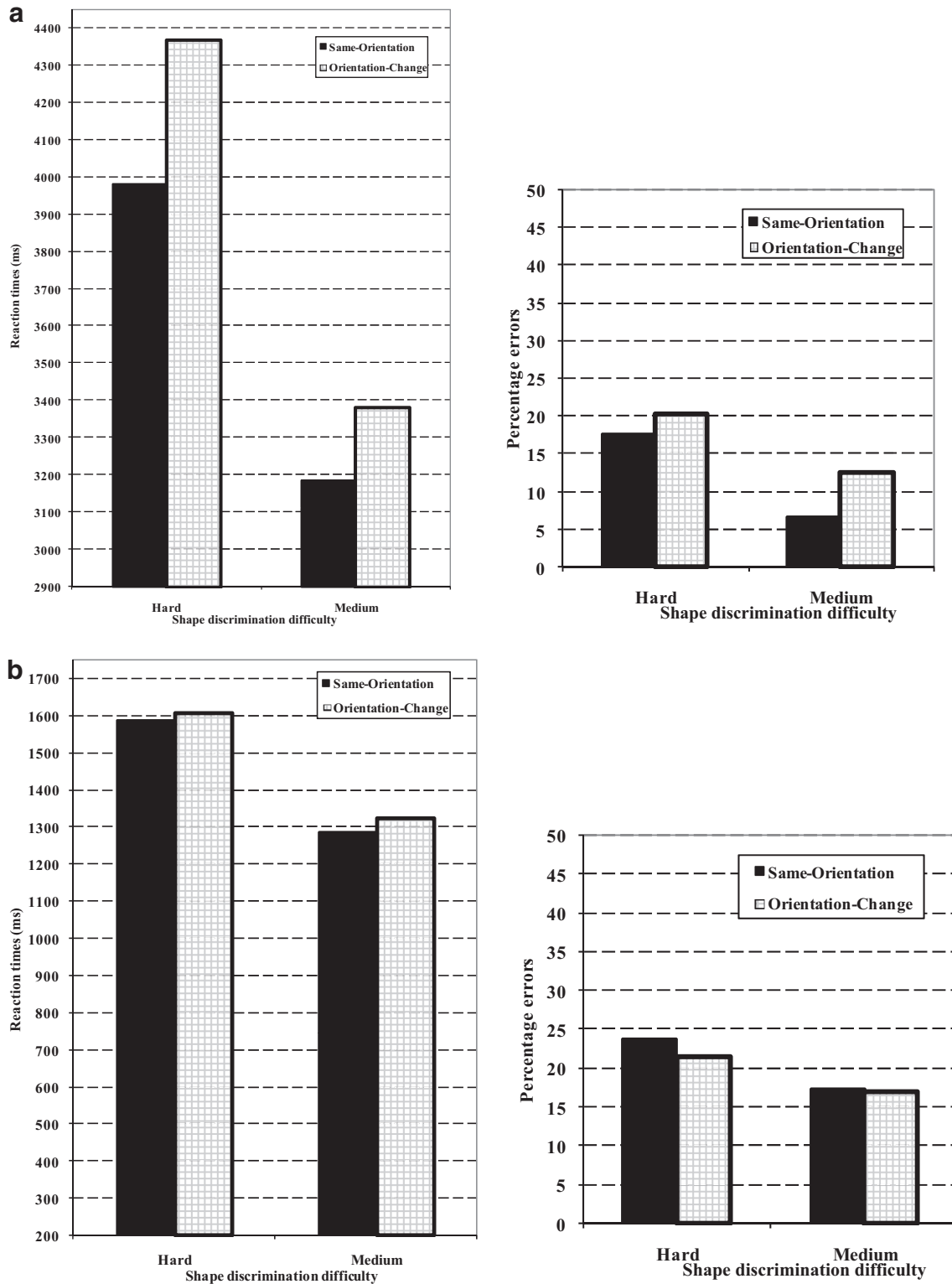


Figure 7. Mean correct reaction times (on the left) and mean percentage errors (on the right) for the two studies of cross-modal matching of three-dimensional familiar objects: (a) Experiment 4 for visual-haptic matching and (b) Experiment 5 for haptic-visual matching. Results are shown for match trials only, for same-orientation and orientation-change trials separately, for the hard and medium shape discrimination groups. Within each study the stimuli presented on match trials were identical across both groups, with only the difficulty of mismatches differing between the groups. As in Experiments 2 and 3, the orientation-change results are for 90° depth rotations.

tion sensitivity was found to differ across within-modal HH and within-modal VV matching in Experiments 2 and 3 here, it was important to investigate whether a similar difference would emerge for cross-modal VH in comparison with cross-modal HV matching. Experiment 5 used the same task, stimuli, and apparatus as were used in Experiments 2–4. The first object was presented haptically, and the second object was presented visually. As in Experiments 3 and 4, two groups were tested, one with a hard shape discriminability task and the other with a medium-difficulty task.

Method

Participants. A total of 32 participants took part in this experiment; all but 1 (in the medium condition) were right-handed.

Materials and apparatus. The materials and apparatus were identical to those used in Experiment 2.

Design and procedure. The design and procedures were identical to those of Experiment 3 except that participants felt the first object (so the first part of the trial was identical to Experiment 2) and then saw the second object (so the second part of the trial was identical to Experiment 3). Of the participants, 16 were assigned to the hard mismatch shape change group, and 16 were allocated to the medium mismatch shape change group.

Results

ANOVAs were conducted on the mean correct RTs and on the percentage of errors for matches and mismatches separately. On matches, same-shape responses were correct, whereas on mismatches, shape-change responses were correct. As in Experiment 3, response latencies of less than 375 ms or exceeding 5,000 ms were discarded as errors (fewer than 1% of trials). No participants were replaced, and there were no empty cells.

Same-shape matches. Orientation change was not significant for either RTs, $F_1(1, 28) = 0.69, p > .40$, partial $\eta^2 = 0.02$, $F_2(1, 18) = 1.42, p > .20$, partial $\eta^2 = 0.07$, or errors $F_1(1, 28) = 0.29, p > .50$, partial $\eta^2 = 0.01$, $F_2(1, 18) = 0.34, p > .5$, partial $\eta^2 = 0.02$. Responses were similar to same-orientation matches (1,437 ms, 20% errors) and 90° orientation-change matches (1,466 ms, 19% errors).

Shape discriminability was significant by items and approached significance by participants, for both RTs, $F_1(1, 28) = 3.62, p < .07$, partial $\eta^2 = 0.11$, $F_2(1, 18) = 82.58, p < .001$, partial $\eta^2 = 0.82$, and errors, $F_1(1, 28) = 2.93, p < .10$, partial $\eta^2 = 0.10$, $F_2(1, 18) = 9.79, p < .007$, partial $\eta^2 = 0.35$. The medium discrimination group (1,306 ms, 17% errors) performed 291 ms faster and 6% more accurately than did the hard discrimination group (1,597 ms, 23% errors), which had to detect smaller shape changes on mismatches. Note that the differences between these two groups were due solely to the mismatch context, as these results were for matches that were identical across both groups.

Finally, the Orientation Change \times Shape Discriminability interaction was not significant for either RTs, $F_1(1, 28) = 0.06, p > .80$, partial $\eta^2 = 0.00$, $F_2(1, 18) = 0.18, p > .60$, partial $\eta^2 = 0.01$, or for errors, $F_1(1, 28) = 0.16, p > .60$, partial $\eta^2 = 0.01$, $F_2(1, 18) = 0.26, p > .60$, partial $\eta^2 = 0.01$ (see Figure 7b). There was no clear orientation sensitivity for either the medium (20 ms, –2% for errors) or the hard (38 ms, 0%) shape discrimination group.

Shape-change mismatches. Mismatches were not the focus of this study, as, unlike matches, different stimuli were presented to the two groups on these trials. Nevertheless, for completeness, these results are reported in brief. Orientation change was not significant for either RTs, $F_1(1, 28) = 0.04, p > .80$, $F_2(1, 18) = 0.12, p > .70$, or for errors, $F_1(1, 28) = 0.05, p > .80$, $F_2(1, 18) = 0.03, p > .80$. Responses were similar to same-orientation matches (1,439 ms, 32% errors) and 90° orientation-change matches (1,446ms, 31%). Shape discriminability was significant for both RTs, $F_1(1, 28) = 9.82, p < .005$, $F_2(1, 18) = 123.09, p < .001$, and errors, $F_1(1, 28) = 32.66, p < .001$, $F_2(1, 18) = 48.45, p < .001$. The medium discrimination group (1,256 ms, 20%) performed 373 ms faster and 22% more accurately than did the hard discrimination group (1,629 ms, 42%). The Orientation Change \times Shape Discriminability interaction was not significant for either RTs, $F_1(1, 28) = 1.17, p > .20$, $F_2(1, 18) = 0.19, p > .60$, or errors, $F_1(1, 28) = 1.30, p > .20$, $F_2(1, 18) = 1.08, p > .30$.

Discussion

In Experiment 5, there was a main effect of shape discriminability, with the hard shape discrimination group performing worse than the medium group. However, neither group showed orientation-sensitive matching. Thus, in clear contrast to the results of HH, VV, and VH matching in Experiments 2, 3, and 4 respectively, HV matching in Experiment 5 was orientation invariant. Performance was no faster or more accurate on same-orientation than on orientation-change trials. This finding replicates the orientation-invariant HV matching reported by Lacey, Peters, and Sathian (2007; but see Newell et al., 2001). These findings are discussed further below.

General Discussion

The results of Experiment 1 demonstrated that haptic exploration of three-dimensional shapes provided sufficient information to name many objects at the basic level when size, texture, rigidity, and other nonshape cues to identity were removed. Experiment 2 found that HH matching of the same objects was orientation sensitive, whether shape discrimination was easy, moderately difficult, or hard. However, there was no interaction between the effects of orientation change and the difficulty of shape discrimination. Experiment 3 replicated Experiment 2 but with visual presentation of the same three-dimensional objects. Here, unlike in Experiment 2, orientation sensitivity for VV matching was greater when shape discrimination was harder. This interaction replicated that found previously in VV matching studies, which presented two-dimensional pictures of three-dimensional objects (Lawson, 2004b; Lawson & Bühlhoff, 2008). Cross-modal matching was explored in Experiment 4 (VH) and Experiment 5 (HV). The results for VH matching replicated the finding of additive effects of orientation change and discriminability found in Experiment 2 for HH matching. In contrast, HV matching was orientation invariant, although performance was still sensitive to the difficulty of shape discrimination. Thus, the modality of stimulus presentation of both the first and the second object on match trials determined whether orientation sensitivity occurred (for VV, HH, and VH, but not for HV, matching) and whether orientation sensitivity interacted with effects of shape discriminability (for VV matching) or

did not (for HH and VH matching). This, in turn, suggests that the orientation sensitivity observed in earlier studies that presented objects haptically (Craddock & Lawson, 2008; Forti & Humphreys, 2005; Lacey, Peters, & Sathian, 2007; Newell et al., 2001) was not due to the same, stored, orientation-specific perceptual representations being accessed irrespective of whether an object was presented visually or haptically. Instead, the present results are consistent with haptic and visual inputs accessing distinct, orientation-sensitive haptic and visual representations of objects. Before returning to discuss why this seems the most plausible interpretation of the present results, I discuss three alternative explanations below.

The first alternative account maintains the assumption that haptic and visual inputs both access the same perceptual object representations. This account proposes that, despite the precautions taken here to equate the information available to both modalities and to match the procedures used to test performance, (a) different information was accessed by haptics and vision and (b) it was this that caused the variation in orientation sensitivity across Experiments 2–5. As already discussed, the first claim is undoubtedly true. For example, often it was the case that different areas of an object were explored haptically than were explored visually. However, the second claim is less convincing. First, the excellent cross-modal performance in Experiments 4 and 5 indicates that much of the same information was coded by both modalities. Second, even if a different subset of features was accessed by haptics and vision, the hard discrimination group always had to distinguish more structurally similar objects, so the same interaction between orientation sensitivity and shape discriminability would still be predicted. It might be countered that, because all sides of an object could be explored haptically in the HH, VH, and HV tasks tested here, that no object-specific orientation sensitivity would be expected. In effect, this would be analogous to showing multiple, depth-rotated views of an object as the first stimulus in a matching task and thus priming all stored views of the object, in which case VV matching would similarly be predicted to be orientation invariant. This extended account would have to explain the haptic orientation sensitivity found for HH and VH matching in Experiments 2 and 4, respectively, as being due to general, non-object-specific priming, as outlined below. However, this latter account of general, rather than object-specific, haptic orientation sensitivity is not consistent with the findings of a recent study reporting object-specific, long-term haptic priming (Craddock & Lawson, 2008). Nevertheless, this alternative explanation cannot yet be conclusively discounted, and further studies are necessary to test it, for instance, by matching the areas of an object explored haptically versus visually.

A similar explanation for the variation in orientation sensitivity dependent on the modality of stimulus presentation is that this was caused by differences in the manner of encoding of visual and haptic information. If so, then the present results would remain consistent with visual and haptic inputs accessing common, stored orientation-specific object representations. For example, for visual stimuli, one whole side of an object frequently can be seen from a single fixation position, so there is often no need to use a sequence of eye movements to acquire sufficient visual information to identify an object. Moreover, people cannot see the far side of an object irrespective of presentation duration. In contrast, manual haptic object exploration is often sequential (Easton, Srinivas, &

Greene, 1997; Loomis, Klatzky, & Lederman, 1991). In Experiments 2 and 3 of the current study, participants typically took several seconds to haptically explore the second object presented on a trial, and with longer presentation durations, people would be more likely to explore all sides of an object. The hard discrimination group responded particularly slowly. The extended presentation duration of the second object for the hard discrimination group allowed them to explore more of the second object than the medium and easy discrimination groups (see Figures 4d and 7). The hard discrimination group was therefore more likely to have exhaustively explored all sides of the second object before responding. This, in turn, could have reduced their orientation sensitivity. In contrast, on same-orientation trials, the medium and, especially, the easy discrimination groups could often respond accurately using only the first few features of the second object that they encountered. Further exploration often might be needed on orientation-change trials only, resulting in orientation-sensitive performance. This hypothesized difference between the amount of the second object explored across the hard, medium, and easy discrimination groups tested with HH and VH matching could have reduced orientation sensitivity for the hard discrimination as compared with the medium and easy discrimination groups. If so, this would produce an interaction between orientation sensitivity and discriminability opposite to that predicted to be caused by the difficulty of shape discrimination per se. The latter interaction between the effects of shape discriminability and orientation sensitivity therefore could have been masked by the former interaction on account of differences in the proportion of the object that was explored. This hypothesis could be tested by restricting the presentation duration or the exploration strategy for the second object on a trial. However, the results of Experiment 5 do not support this alternative explanation of the lack of an interaction between shape discriminability and orientation sensitivity in Experiments 2 and 4. In Experiment 5, orientation-sensitive performance would be expected if the same-orientation benefit in Experiments 2, 3, and 4 was due to both visual and haptic inputs accessing a common, orientation-specific object representation. Contrary to this prediction, HV matching in Experiment 5 was orientation invariant.

A more plausible explanation for the pattern of results found in Experiments 2–5 is that the same-orientation benefit reflects access to orientation-sensitive representations for visual, but not for haptic, object recognition. For visual presentation, this leads to superior performance on same-orientation trials, particularly when structurally similar shapes must be distinguished. If shape discrimination is easier, then coarse, orientation-invariant information will sometimes suffice to distinguish between objects, leading to reduced orientation sensitivity (Lawson, 2004b; Lawson & Bühlhoff, 2008). This explains the interaction of orientation sensitivity with shape discriminability found for VV matching. In contrast, on this account, haptic object representations are assumed to be orientation invariant, which explains why HV matching was orientation invariant.

However, this account needs to be extended in order to explain the results for HH and VH matching. One possibility is that the orientation sensitivity found here could be due to general, spatial priming effects rather than to matching to stored, orientation-sensitive perceptual representations of objects. When people reach for an object that they cannot see, they might tend to use the spatial location of the previous object that they have felt to guide their

hand movement. If so, then for both VH and HH matching, this spatial priming should benefit same-orientation trials (as the hand would reach directly toward the most important part of the second object presented on a trial) relative to orientation-change trials (where the hand might take longer to locate the second object in space and/or the fingers might initially touch an uninformative area of the second object and then have to explore further to locate distinguishing information). An additional reason for the orientation sensitivity for HH and VH matching may be that haptic objects are coded with respect to a main axis (e.g., the primary axis of elongation; see Craddock & Lawson, 2008). People may be better at finding the location of this axis on same-orientation trials if they used the location of this axis for the first object to guide their search for the axis of the second object. This account could be tested by mis/cueing people about the upcoming location or orientation of the second object on a trial. Alternatively, objects could be randomly located so that on same-orientation trials participants could not benefit by using the spatial location of the first object on a trial to guide their hand movements. Note that for vision, any such effects of finding objects in space or of assigning axes are likely to be much weaker because the cost (in terms of both time and effort) of extracting object location and orientation information visually is much less.

However, if haptic orientation sensitivity is due to such general, spatial priming effects rather than to the involvement of perceptual object representations, then this would provide evidence against the hypothesis that haptic and visual inputs access common perceptual representations. This is because, as reviewed in the introduction, long-term priming studies (e.g., Lawson & Humphreys, 1998) provided evidence that visual object representations are orientation sensitive. Hence, if the haptic orientation sensitivity found in the present studies is caused by general spatial cueing rather than by object-specific priming, this would suggest that haptic stored object representations are orientation invariant. Furthermore, this latter conclusion is not consistent with the orientation-sensitive performance reported for a long-term old-new haptic object recognition memory task (Craddock & Lawson, 2008). In Craddock and Lawson's study, several minutes and a large number of items separated the two presentations of a given object, so general (as opposed to object-specific) priming effects cannot explain why there was superior performance on same-orientation trials.

The only hypothesis that is consistent with both the present, short-term matching results and the long-term memory results of Craddock and Lawson (2008) is that objects presented visually and haptically access modality-specific visual and haptic object representations, respectively, with both types of representation being orientation sensitive. In order to explain the excellent cross-modal performance reported here and in earlier research, it is necessary to assume that these representations can either be accessed efficiently via the other modality or that cross-modal recognition is mediated by common, multimodal object representations. The difference between orientation-sensitive VH and orientation-invariant HV cross-modal matching found in Experiments 4 and 5 here suggests that haptic stimuli may be matched to orientation-sensitive visual representations but that visual stimuli are matched to common, orientation-invariant object representations.

The issues raised in this General Discussion serve to highlight the problems inherent in attempting to compare performance

across modalities. Alternative accounts, such as those outlined above, must be tested, and the present results need to be replicated with different stimuli and tasks before the tentative conclusions drawn above can be accepted. It is obviously difficult to make direct comparisons between visual and haptic object recognition. This is the case even if the same stimuli are tested in the same design with the same apparatus, as was the case in Experiments 2–5 here. Factors such as the orientation of an object and how long it is exposed cannot be matched straightforwardly across the modalities. This is not merely a consequence of technical problems but is also due to fundamental differences across vision and haptics in terms of the type of information that can be detected and how it is acquired. Nevertheless, it is possible to design studies that minimize differences between the two modalities, for example, by restricting the type of information available, either by including carefully controlled stimuli (as in the shape-defined objects used in the present studies) or by reducing or restricting access to certain features of the stimuli (e.g., Klatzky et al., 1993; Klatzky & Lederman, 1995; Lederman & Klatzky, 2004; Loomis et al., 1991; Newell et al., 2001; see Jones & Lederman, 2006).

The present studies provide an important comparison between visual and haptic object recognition. Two variables known to have strong effects on visual object recognition were manipulated, namely, orientation in depth and shape discriminability. The combined effects of these variables were tested for within-modal and cross-modal object recognition with a standard task taken from visual object recognition research and well-controlled, nameable, stimuli. The results suggest that the superficial similarities in achieving visual versus haptic object recognition reviewed in the introduction may be misleading, as the effects of discriminability on orientation sensitivity differed strikingly depending on the modality of stimulus presentation. These findings provide evidence against the hypothesis that the same orientation-sensitive perceptual representations are accessed for both visual and haptic object recognition and instead suggest that the cause of orientation sensitivity differs for visual versus haptic object recognition. However, the caveats discussed above to the interpretation of the present results render this conclusion preliminary. Further empirical research is necessary to fully map out the effects of depth rotation on haptic object processing.

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