Atten Percept Psychophys (2014) 76:541–558
DOI 10.3758/s13414-013-0559-1

Recognizing familiar objects by hand and foot: Haptic shape perception generalizes to inputs from unusual locations and untrained body parts

Rebecca Lawson

Abstract The limits of generalization of our 3-D shape recognition system to identifying objects by touch was investigated by testing exploration at unusual locations and using untrained effectors. In Experiments 1 and 2, people found identification by hand of real objects, plastic 3-D models of objects, and raised line drawings placed in front of themselves no easier than when exploration was behind their back. Experiment 3 compared one-handed, two-handed, one-footed, and two-footed haptic object recognition of familiar objects. Recognition by foot was slower (7 vs. 13 s) and much less accurate (9 % vs. 47 % errors) than recognition by either one or both hands. Nevertheless, item difficulty was similar across hand and foot exploration, and there was a strong correlation between an individual's hand and foot performance. Furthermore, foot recognition was better with the largest 20 of the 80 items (32 % errors), suggesting that physical limitations hampered exploration by foot. Thus, object recognition by hand generalized efficiently across the spatial location of stimuli, while object recognition by foot seemed surprisingly good given that no prior training was provided. Active touch (haptics) thus efficiently extracts 3-D shape information and accesses stored representations of familiar objects from novel modes of input.

Keywords Haptic · Object · Recognition · Hand · Foot

Introduction

We are remarkably able at recognizing everyday objects, such as teapots, bananas, and staplers, by touching them with our hands while blindfolded (Klatzky, Lederman, & Metzger, 1985). This skill appears to depend mainly on 3-D shape perception, because even plastic scale models of familiar objects are identified quite accurately despite lacking other cues to their identity, such as size, texture, and material (Lawson & Bracken, 2011). Given how rarely we rely solely on feeling objects to identify them, we seem unnecessarily good at recognition using our sense of active touch (haptics). One plausible reason for this level of expertise and our ability to recognize objects haptically that we have only seen before (e.g., Lawson, 2009) is that haptics can harness the same powerful and highly trained processes used by our visual object recognition system, so that haptics itself requires few dedicated neural resources.

There is, though, a significant barrier to such sharing of resources across modalities in that visual and haptic inputs are radically different in terms of the nature of the receptors used by vision and touch and in terms of the spatial and temporal acquisition of information by each modality. For shape information to be shared by both modalities, the internal representations arising from the same physical object, but based on visual versus haptic inputs, would either need to be remapped into a common spatial reference system, or information from multiple reference frames would need to be combined (Volcic, Wijntjes, Kool, & Kappers, 2010). This difficult task may be achieved because we have had a lifetime of experience of seeing objects in front of us at the same time as touching them, as we use tools, choose and prepare food, and so on. Processing thousands of hours of simultaneous visual and haptic inputs arising from interactions with the same object may allow us to fine-tune the complex mapping between these inputs and, perhaps, to acquire shared, visuo-haptic

R. Lawson
School of Psychology, University of Liverpool, Liverpool, UK

R. Lawson (✉)
Department of Experimental Psychology, University of Liverpool,
Eleanor Rathbone Building Bedford Street South,
Liverpool L69 7ZA, UK
e-mail: rlawson@liv.ac.uk

representations of the 3-D shape of familiar objects in common spatial coordinates. Indeed, some evidence suggests that this mapping may be established, at least coarsely, without extensive coupled visuo-haptic inputs, whether in infancy or in the congenitally blind if sight is restored, as well as following disruption to an established mapping in prism adaption studies (Held, 2009).

There is mounting evidence to support this hypothesis. For example, behavioral studies indicate that vision and haptics using the hands make use of shared perceptual representations and processes in order to analyze object shape (Gaissert & Wallraven, 2012; Lawson, Boylan, & Edwards, In press) and that 3-D shape information readily transfers from vision to touch and vice versa (Easton, Srinivas, & Greene, 1997; Lawson, 2009; Norman, Clayton, Norman, & Crabtree, 2008; Norman, Norman, Clayton, Lianekhammy, & Zielke, 2004; Phillips, Egan, & Perry, 2009; Reales & Ballesteros, 1999; Yildirim & Jacobs, 2013). Furthermore, inputs from vision and touch may be localized into common external spatial coordinates (Heed, Backhaus, & Roder, 2012). Recent imaging studies have indicated that there is considerable overlap in the ventral occipito-temporal areas activated during visual and haptic object recognition tasks (Amedi, Jacobson, Hendler, Malach, & Zohary, 2002; Amedi, Malach, Hendler, Peled, & Zohary, 2001; Lucan, Foxe, Gomez-Ramirez, Sathian, & Molholm, 2010; Miquée et al., 2008). The lateral occipital complex (e.g., Amedi et al., 2002; Amedi et al., 2001; Deibert, Kraut, Kremen, & Hart, 1999; James, Kim, & Fisher, 2007; Miquée et al., 2008; Sathian & Lacey, 2007; Tal & Amedi, 2009) and the intraparietal sulcus (e.g., Stilla & Sathian, 2008; Zhang, Weissser, Stilla, Prather, & Sathian, 2004) seem to be particularly important. This overlap provides evidence that modality-independent, supramodal, or crossmodal representations support both visual and haptic object recognition (Allen & Humphreys, 2009; Amedi, Raz, Azulay, Malach, & Zohary, 2010; Lacey, Tal, Amedi, & Sathian, 2009; Ricciardi & Pietrini, 2011).

The above account explains why we are so good at recognizing objects by touching them with our hands. However, the question remains as to whether our skill at this task is a special case that occurs only because of our extensive experience of integrating visual inputs (from seeing an object in front of us) with haptic inputs (arising from exploring that same object using our hands). The present experiments investigated whether haptic object recognition becomes much more difficult when familiar, nameable objects are felt under different circumstances with which we have had little or no prior experience. In our first two experiments, objects were felt at a location that we cannot usually observe (behind our back), and in the final experiment, objects were felt by a body part (the foot) that is not usually used to explore 3-D shape.

Generalization of haptic object recognition to these novel situations should not occur if access to stored, visuo-haptic representations of familiar objects relies on having extended experience of simultaneous inputs from the eyes and the hands as they extract information from the same physical object held in front of us. This account assumes that an accurate spatial mapping is only gradually established between a particular type of haptic input and stored 3-D object representations and, further, that this established mapping cannot be generalized to be used to process other haptic inputs. If, contrary to this prediction, even unfamiliar haptic inputs can be interpreted accurately after little or no training, it would indicate that haptic processing is flexible and can easily be configured to allow matching to stored object representations that were acquired from very different sensory inputs. This, in turn, would be consistent with more general claims that a supramodal or crossmodal object recognition system subserves both visual and haptic identification (Allen & Humphreys, 2009; Amedi et al., 2010; Lacey et al., 2009; Ricciardi & Pietrini, 2011).

In Experiment 1, people used both of their hands to recognize and name real, familiar objects that were presented in front, to the side, and behind themselves and when their hands were crossed over. Haptic object recognition using the hands was remarkably tolerant to the position of the object relative to the body. In Experiment 2, this finding was extended to right-handed naming of 3-D models of familiar objects and naming of raised line drawings of familiar objects that were presented in front, to the side, and behind people. Experiment 3 compared right-handed, both-handed, right-footed, and both-footed naming of real, familiar objects. Haptic object recognition using the feet was much harder than by hand, yet around half of the objects could still be identified, so foot recognition was surprisingly effective. These results demonstrate that our visuo-haptic object-processing system can successfully extract shape information from a broad range of inputs, including those arising from rarely experienced spatial locations (such as behind the back) and from untrained body parts (such as the feet).

Experiment 1

Our hands can identify real 3-D objects quite quickly and accurately even with no visual input. Klatzky et al. (1985) tested people's ability to identify real, familiar objects haptically. They allowed people to pick up and manipulate the objects. They reported naming errors under 5 % and reaction times (RTs) that were typically under 3 s. Studies that have not allowed people to pick up or to move objects have reported somewhat slower performance, so information about an object's weight and moving parts seems to be important for recognition. Nevertheless, recognition performance remains good. For example, Lawson et al. (In press) and Craddock and Lawson (2008, 2009b) reported 4 %–12 % errors and RTs of

3–5 s for naming real, familiar objects fixed to tiles, while in their baseline study, Klatzky, Loomis, Lederman, Wake, and Fujita (1993) reported 5 % errors and RTs of 6 s. However, none of these studies manipulated the location of the object in relation to the participant.

The hands can usually easily explore all sides of an object, provided that it is not too large. Nevertheless, it is now well established that haptic object recognition is sensitive to the orientation of the object in depth (Craddock & Lawson, 2008; Ernst, Lange, & Newell, 2007; Lacey, Peters, & Sathian, 2007; Lawson, 2009, 2011; Newell, Ernst, Tjan, & Bülthoff, 2001). This suggests that haptic object representations are not coded in an object-centered coordinate system; instead, haptic representations must include information about the orientation with respect to the body or to the environment in which an object is presented. In addition, haptic object perception is sensitive to the size of the object (Craddock & Lawson, 2009b, c). Extending this line of research, Experiment 1 investigated whether haptic object recognition is also influenced by the position of an object in space, to test whether haptics achieves invariance over spatial location, relative to the body or the environment. As far as I am aware, this has never been investigated. Sensation at a given fingertip must be interpreted very differently depending on where the fingers are relative to the hand and where the hand is relative to the body (Heed et al., 2012), and these positions vary enormously depending on the location in space of the object being touched. Thus, achieving invariance over spatial location is nontrivial.

In Experiment 1, participants used both hands to explore real, familiar objects in each of four conditions: Objects were placed in front, 90° to the right side, or directly behind the back of participants, or they were placed in front of the participant but were explored using crossed hands (see Fig. 1). If the haptic system can interpret inputs from novel locations (side and, especially, back) just as easily as from a highly familiar (front) location, it would suggest that there is an efficient remapping of haptic inputs arising from novel locations that permits those inputs to be matched to preexisting stored object representations. In contrast, if previous experience is important for learning a particular remapping, people should find it much easier to name objects presented in the usual front location than to name objects explored in the rarely experienced behind location. The crossed-hand condition was included as a control for the behind condition. Object exploration behind the back and with crossed hands were both expected to be more awkward (due to anatomical constraints) than in the front and side positions. However, the crossed-hand condition presented objects in the normal front location, whereas the behind condition involved an unusual, untrained location.

Fig. 1 *Top*: Setup used in Experiment 1 showing the three object locations tested (front, right side, and behind). The participant shown has his hands in the start position for a side object trial with the vinegar bottle. *Bottom*: Participant feeling an object in the behind position

Method

Participants

Thirty-two student volunteers took part in the study (all self-reported as right-handed; 8 were male; mean age was 20 years).

Materials and apparatus

Sixty-four familiar, nameable objects were presented. Each was mounted on a ceramic tile or a plastic CD case. An arrow on the tile or case indicated the front of the object. The objects were placed on surfaces in front, to the right, and behind the participant such that the arrows pointed in toward the participant (see Fig. 1). Objects were thus oriented so that the front of the object always faced the participant. The behind location was 20 cm lower than the front and side locations, since this was the most comfortable height for participants. Participants were told before each trial where the object would be placed, and they were instructed to rest their right and left hands on the nearest corner of the relevant surface in preparation for each trial. Before entering the experimental room, participants put on a mask that blocked their view of the room but allowed some diffuse light to enter.

Design

The 64 objects were divided into four sets, with every object being presented just once to each participant. Allocation of the four conditions (front, side, behind, and crossed) to these sets was counterbalanced across participants using a Latin square design. The 64 experimental trials were divided into subsets of four trials, and within each subset, 1 object was presented in each of the four conditions. These subsets of 4 trials were presented in one fixed order to half the participants and in the reverse order to the remaining participants.

Procedure

On each trial, the experimenter placed the object in the appropriate location and said to the participants “front,” “side,” “back,” or “crossed.” The experimenter then pressed a key on the computer keyboard to trigger a single low-pitched warning beep, which was followed after 1 s by a high-pitched double beep that indicated that the participants could start to move their hands from their resting positions to touch the object. People were not allowed to rotate, move, or pick up the object. They had unlimited time to name it but were instructed to respond as rapidly as possible and to guess if necessary. RTs were measured from the offset of the double beep to the onset of the participant’s naming response using a microphone headset placed on the participants’ head and attached to a Macintosh computer. The experimenter recorded trials on which participants made naming or other errors. The experimental trials were preceded by 15 practice trials, which were tested using a mixture of the four conditions and which used a different set of objects. Feedback was provided on the practice trials (but not the experimental trials) by telling participants if they were correct and, if not, by telling them the name of the object that they had just felt. The experiment took around 45 min to complete. Afterward, people were asked whether they had seen any of the stimuli.

Results

No participants said that they had seen any of the objects, and no participants were replaced. Correct RTs shorter than 1 s or longer than 20 s were removed as outliers (fewer than 1 % of trials). ANOVAs were conducted on the mean correct RTs and on the percentages of errors (see Fig. 2). There was one within-subjects and within-items factor of *position* (normal hands and object in front, at the side, or behind or crossed hands and object in front). Here, and in Experiments 2 and 3, the results for the F-value in the by-participants and by-items analyses are reported using subscripts F_p and F_i, respectively, and unless otherwise stated, all pairwise differences noted were significant ($p < .05$) in by-participants and by-items post hoc Newman–Keuls analyses.

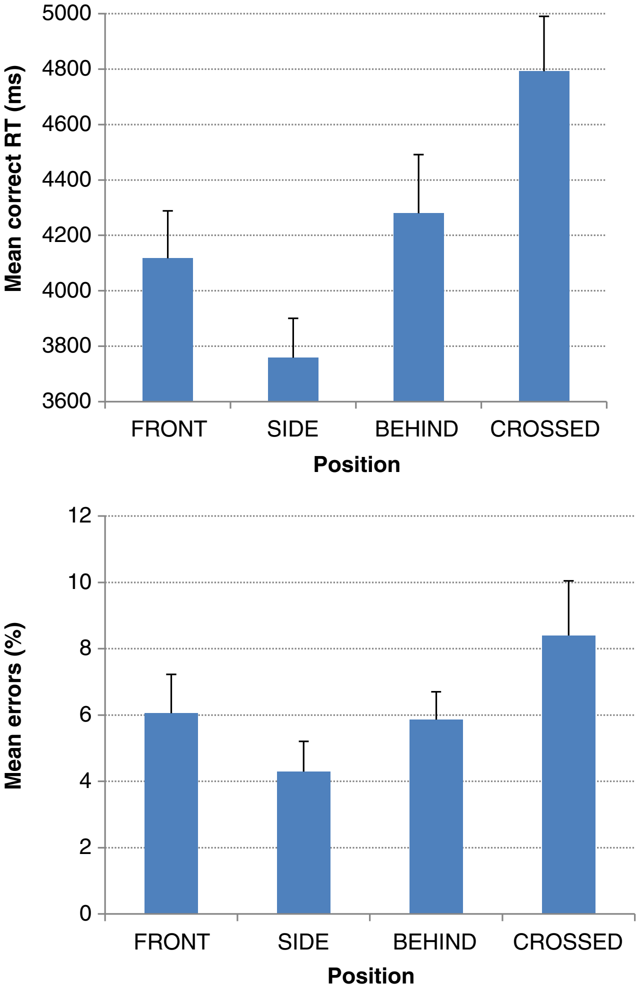

Fig. 2 Mean correct response times (RTs, in milliseconds) (*top*) and percentages of errors (*bottom*) in Experiment 1 for the four positions (front, side, behind, and in front with the hands crossed). Error bars show 1 standard error of the mean

The main effect of position was significant for both RTs, $F_p(3, 93) = 13.651$, $p = .000$, partial $\eta^2 = .31$; $F_i(3, 189) = 18.562$, $p = .000$, partial $\eta^2 = .23$, and errors, although only marginally for participants, $F_p(3, 93) = 2.409$, $p = .07$, partial $\eta^2 = .07$; $F_i(3, 189) = 2.994$, $p = .03$, partial $\eta^2 = .05$.

People were slower at naming objects with crossed hands (4,792 ms, 8.4 % errors), relative to the other three conditions. Unexpectedly, people were faster at naming objects at their side (3,759 ms, 4.3 %) than at any other position. Most important, there was no significant difference between the front (4,117 ms, 6.1 %) and behind (4,280 ms, 5.9 %) conditions. There was no evidence for a speed–accuracy trade-off. For errors, the only significant difference in the post hoc Newman–Keuls tests for items was that fewer errors were made in the side condition than in the crossed-hands condition.

Discussion

People's ability to name real, familiar objects by touch was similar regardless of the physical location of the object relative to their body. RTs were under 5 s and errors under 10 % in all of the conditions tested. Most strikingly, people identified objects behind their back just as quickly and accurately as objects presented in front of them. This finding was unexpected for several reasons. First, people rarely need to identify objects behind their back, so this was a novel task for them. Also, people reported that it was physically rather awkward to explore objects behind their back. In addition, their gaze was always directed at least 90° away from their hands in the behind condition, and yet recognition of both 3-D objects and 2-D raised line drawings has been found to be harder when gaze is misaligned with haptic inputs, even when the hands and the object are not visible (Lawson et al., In press; Scocchia, Stucchi, & Loomis, 2009). Finally, on the basis of results from a tactile spatial attention selection task, Gillmeister and Forster (2012) suggested that proprioceptive space may wrap around the body so that, when the hands are close together behind the back, their positions are represented internally as being maximally distant from each other. This result suggests that it should be harder to integrate information from both hands in the behind condition. Nevertheless, there was no evidence of a cost for recognizing objects presented at the least familiar, behind location in Experiment 1. Our tolerance to variation in the spatial location of an object was reexamined in Experiment 2, using a task that was designed to increase sensitivity for detecting position effects by using stimuli that could be identified only by using shape information and by using unimanual exploration.

People in Experiment 1 were worse at identifying objects when their hands were crossed. However, even this cost was modest. Furthermore, at least part of this difficulty probably arose from people having to continually monitor themselves to avoid their natural inclination to uncross their hands. Participants occasionally had to be reminded by the experimenter about this, and this monitoring may have meant that the crossed-hand condition was akin to doing a dual task. There may, though, also be a specific difficulty in representing haptic shape information when the hands are crossed. Evidence from temporal order judgment tasks indicates that crossing the hands influences our interpretation of tactile information because hand position is recoded into external spatial coordinates (Heed et al., 2012). If asynchronous tactile stimulation is given to fingers on different hands, the just-noticeable difference in deciding which hand was touched first is substantially larger with crossed hands than with uncrossed hands. This is the case even when the response does not require any remapping—for example, if people respond just by moving the hand that was touched first (Schicke & Röder, 2006). Tactile remapping across the postural changes arising from crossing the hands appears to develop in early infancy (Bremner, Mareschal, Lloyd-Fox, & Spence, 2008) and occurs automatically (Azañón, Camacho, & Soto-Faraco, 2010) and rapidly (in under 300 ms; Overvliet, Azañón, & Soto-Faraco, 2011; Yamamoto & Kitazawa, 2001). Furthermore, Kobor, Furedi, Kovacs, Spence, and Vidnyanszky (2006) found that temporal order discrimination was worse with crossed, relative to uncrossed, hands even when people's hands were behind their backs and, so, in an area of space that is never visible, suggesting that tactile inputs are not just remapped into a visual coordinate system. However, this crossed-hands effect was weaker behind the back than when people had their hands in front of themselves. In addition, Roder, Rosler, and Spence (2004) found a crossed-hand effect for late blind people, but not for congenitally blind people (see also Collignon, Charbonneau, Lassonde, & Lepore, 2009). Together, these results suggest that visual recoding does play a significant role in the crossed-hands effect.

Experiment 2

Experiment 2 sought to replicate the most surprising result of Experiment 1—namely, that we can recognize objects presented behind our backs just as effectively as objects felt directly in front of us. Experiment 2 also tested whether the unexpected finding of a benefit for the side position, relative to the front position, was reliable. Three positions were tested: front, side, and back. Two main changes were made in Experiment 2, as compared with Experiment 1, to try to increase its sensitivity to effects of object location.

First, participants were only allowed to use their right hand to feel the objects. Using both hands together to feel an object, as in Experiment 1, may provide a strong egocentric spatial reference frame that is consistent with that used in everyday life. This salient and familiar reference frame may, in turn, alleviate any difficulty in representing objects presented at unusual spatial locations. Requiring people to use only one hand in Experiment 2 might, therefore, make it easier to detect small effects of variation in spatial position.

Second, two new sets of items were tested, both of which were expected to be more sensitive to effects of spatial location than were the real, familiar objects tested in Experiment 1. One group of participants felt 3-D, hand-sized plastic models of familiar, nameable objects. These stimuli lacked the position-invariant cues to identity (such as texture, heat conductance, and compliance) that were available from the real objects tested in Experiment 1 because these models were all made of the same material. These stimuli thus had the same texture, compliance, and so on, and they also all had a similar size. Real objects are substantially easier to identify than plastic models, indicating that these position-invariant cues are important for haptic object recognition (Lawson et al., In press; Lawson & Bracken, 2011). The greater the reliance of haptic object recognition on position-invariant cues, then, the weaker any effect of spatial location is expected to be. The haptic recognition of plastic models must rely solely on extracting an accurate 3-D shape representation, since no other cues to identity are available. Thus, if haptic object recognition is sensitive to the location at which objects are presented, these location effects should be easier to detect using plastic models than using real, familiar objects. The second group of participants in Experiment 2 tried to identify raised line drawings of familiar objects. Such stimuli are extremely difficult to identify haptically (Lawson & Bracken, 2011), and their recognition is known to be significantly enhanced when the head is directed to look toward them (Lawson et al., In press; Scocchia et al., 2009), so any disadvantage for the behind position may be easier to detect with such stimuli.

Method

Participants

Thirty-six student volunteers took part in the study (all but 2 self-reported as right-handed; 6 were male; mean age was 19 years).

Materials and apparatus

Two versions of each of 27 familiar, nameable objects were used. The stimuli were printed in rigid white plastic using a Dimension 3-D acrylonitrile butadiene styrene plastic printer (Dimension, Inc., Eden Prairie, MN). The raised line drawing stimuli had to lie on their side in order to be placed flat, and the 3-D models were positioned to match the orientation of the drawings (see Fig. 3), in contrast to the objects in Experiment 1, which were placed upright (see Fig. 1). Each stimulus was mounted on a plastic CD case, and yellow tape on the case indicated the bottom of the stimulus (see Fig. 3). Stimuli were placed on surfaces in front, to the right, and behind the participant such that the yellow tape always pointed in toward the participant. Stimuli were thus oriented so that their base was always the nearest side to the participant and the top was farthest away. The behind location was 20 cm lower than the front and side locations, since this was the most comfortable height for participants. Participants were told before each trial where the stimulus would be placed, and they were instructed to rest their right hand on the nearest corner of the relevant surface in preparation for each trial. Before entering the experimental room, participants put on a mask that blocked their view of the room but allowed some diffuse light to enter. They were instructed to look straight ahead throughout the experiment.

Design

Each of the 27 objects was presented just once to each participant; half the participants felt 3-D models, and the other half felt raised line drawings. The stimuli were divided into three sets of nine items. Allocation of the three conditions (front, side, and behind) to these sets was counterbalanced across participants using a Latin square design. The 27 experimental trials were divided into subsets of 3 trials, and within each subset, one stimulus was presented in each of the three conditions. These subsets of 3 trials were presented in one fixed order to half the participants and in the reverse order for the remaining participants, giving six conditions for the 3-D model group and six for the raised line drawing group.

Procedure

On each trial, the experimenter placed the stimulus in the appropriate location and said to the participants “front,” “side,” or “back.” The experimenter then pressed a key on the computer keyboard to trigger a single warning beep, which was followed after 1 s by the words “go now,” which indicated that the participants could start to move their right hand from its resting position to touch the stimulus. People were not allowed to rotate, move, or pick up stimuli. They had unlimited time to name the stimuli but were instructed to respond as rapidly as possible and to guess if necessary. RTs were measured from the onset of the “go now” signal to the onset of the participants’ naming response and were recorded using a microphone headset placed on the participants’ head and attached to a PC computer. There were no practice trials. The experimenter recorded trials on which participants made naming or other errors. The experiment took around 35 min to complete. Afterward, people were asked whether they had seen any of the stimuli.

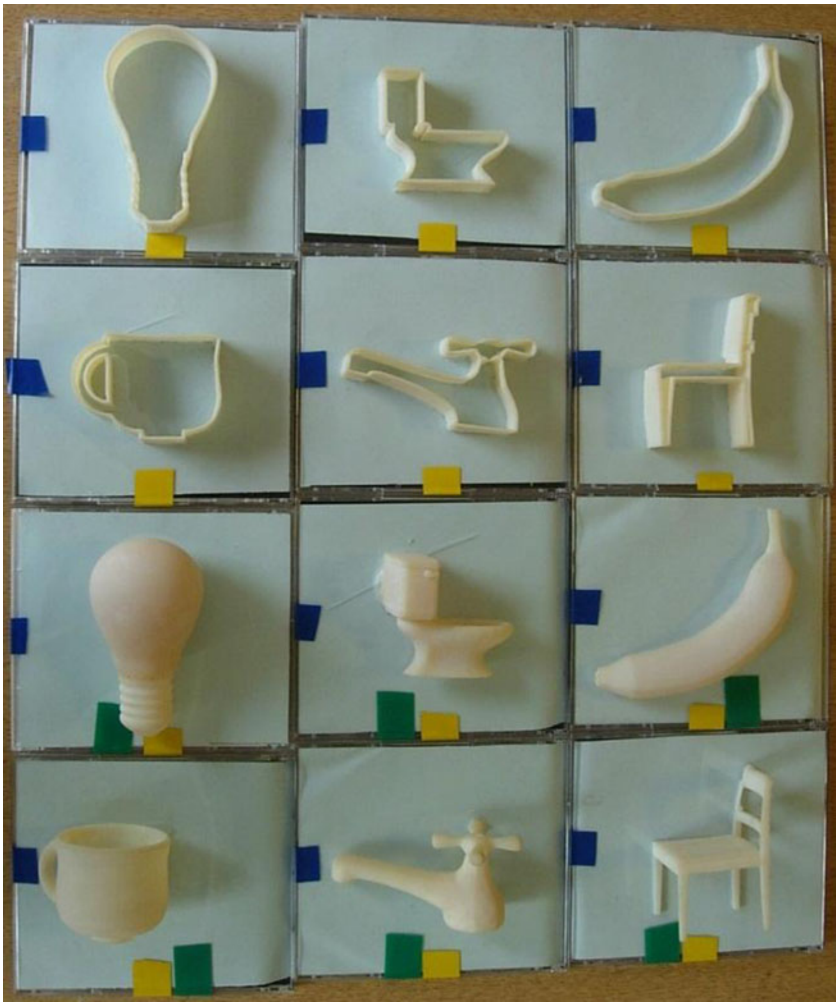

Fig. 3 Examples of 6 of the 27 objects presented in Experiment 2 (lightbulb, toilet, banana, cup, tap, and chair), represented by raised line drawings (*top*) and 3-D models (*bottom*)

Results

No participants said that they had seen any of the stimuli, and no participants were replaced. Correct RTs shorter than 1 s or longer than 50 s were removed as outliers (fewer than 1 % of trials). ANOVAs were conducted on the mean correct RTs and on the percentages of errors (see Fig. 4). There was one within-subjects and within-items factor of *position* (front, side, or behind) and one between-subjects but within-items factor of *stimulus* (3-D models or raised line drawings).

The main effect of stimulus was significant for both RTs, $F_p(1, 34) = 6.840$, $p = .01$, partial $\eta^2 = .17$; $F_i(1, 26) = 35.688$, $p = .000$, partial $\eta^2 = .58$, and errors, $F_p(1, 34) = 27.306$, $p = .000$, partial $\eta^2 = .45$; $F_i(1, 26) = 40.447$, $p = .000$, partial $\eta^2 = .61$. As was expected, people were both faster (11.5 s, as compared with 16.0 s) and much more accurate (35.5 % errors, as compared with 67.8 %) at naming the 3-D models than at naming the raised line drawings.

The main effect of position was significant for RTs, although only marginally for participants, $F_p(2, 68) = 2.773$, $p = .07$, partial $\eta^2 = .08$; $F_i(2, 52) = 3.274$, $p = .05$, partial $\eta^2 = .58$, and it was significant only for items for errors, $F_p(2, 68) = 1.569$, $p = .2$, partial $\eta^2 = .04$; $F_i(2, 52) = 3.274$, $p = .05$, partial $\eta^2 = .11$. There were no large differences between the three positions in speed (13.3, 12.9, and 14.9 s for stimuli presented to the front, side, and back, respectively) or in accuracy (53.0 %, 48.3 %, and 53.7 % errors). The only significant difference in the by-items post hoc Newman–Keuls analyses for RTs and errors was that people were faster for the side than for the back position.

The stimulus × position interaction was not significant for RTs, $F_p(2, 68) = 1.275$, $p = .2$, partial $\eta^2 = .04$; $F_i(2, 52) = 0.129$, $p = .8$, partial $\eta^2 = .01$, or for errors, $F_p(2, 68) = 0.322$, $p = .7$, partial $\eta^2 = .01$; $F_i(2, 52) = 0.267$, $p = .7$, partial $\eta^2 = .01$ (see Fig. 4).

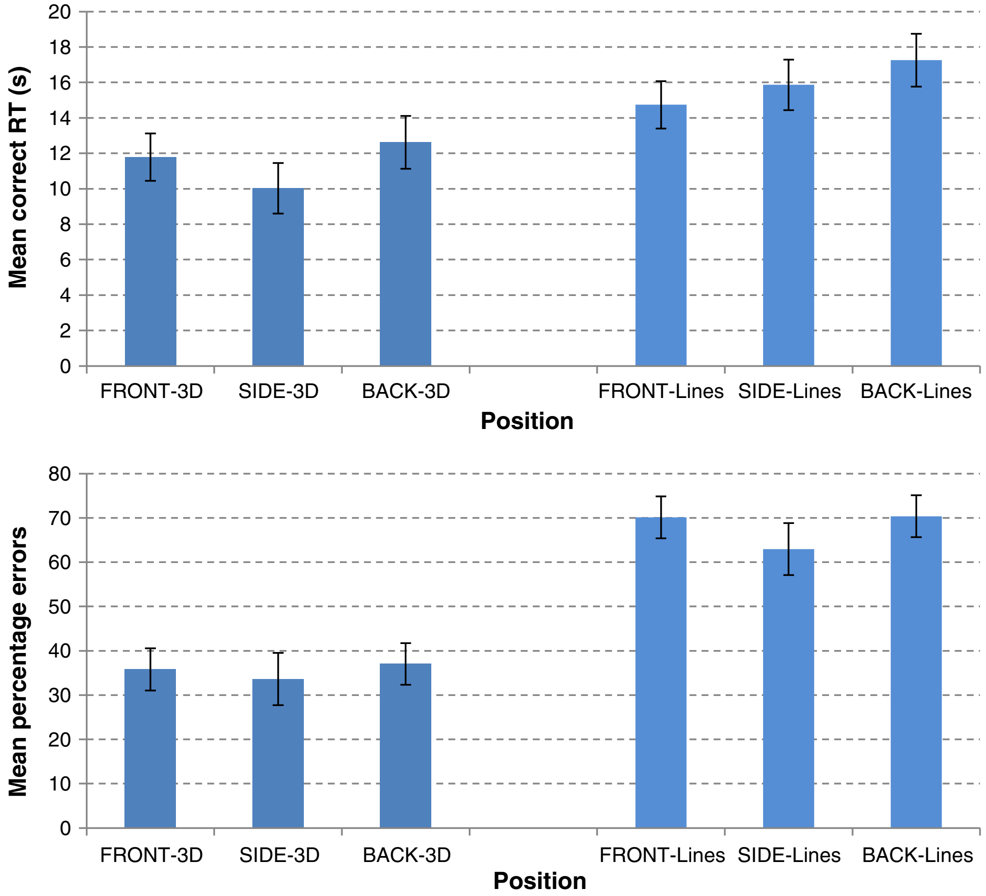

Fig. 4 Mean correct response times (RTs, in milliseconds) (*top*) and percentages of errors (*bottom*) in Experiment 2 for the three positions (front, side, and behind) for the group presented with 3-D models of objects (*left*) and the group presented with raised line drawings of objects (*right*). Error bars show 1 standard error of the mean

Discussion

As was expected, people found it much harder to name the raised line drawings (16.0 s, 67.8 % errors) than the plastic 3-D models (11.5 s, 35.5 % errors), which, in turn, were harder to name than the real, familiar objects presented in Experiment 1 (4.2 s, 6.1 % errors). This demonstrates, respectively, the importance of depth cues (Lawson & Bracken, 2011) and of position-invariant cues (such as texture, compliance, and heat conductance) to haptic processing.

Most important the results of Experiment 2 replicated those of Experiment 1 in that haptic object recognition was similar across the three spatial locations tested. Strikingly, once again people were no faster or more accurate in recognizing stimuli placed in front of them, as compared with stimuli felt behind their back. As in Experiment 1, there was a weak benefit for the side position. This finding was unexpected, and further work will be needed to determine the cause of this effect.

An even more powerful experimental design than that used in Experiment 2 might reveal a subtle cost for recognition in the behind, relative to the front, position. However, it would be difficult to demonstrate that any such small difference between these two positions was due solely to spatial position, because it is hard to closely match all other aspects of testing. For example, in the behind position, the most comfortable hand orientation is with the wrists uppermost and fingers below and pointing down (see Fig. 1), whereas in the front and side positions, the wrists and fingers are typically approximately level during haptic exploration and the wrists are much nearer to the body than are the fingers. These differences in posture will influence how an object is explored and which shapes and features of an object are most accessible, and this, rather than variation in spatial location per se, might change haptic object processing.

Experiment 3

The most important finding from the first two experiments was the similarity of haptic object recognition for exploration at the familiar front position and the novel, unpracticed behind position. This was true for bimanual, as well as unimanual, exploration and for the recognition of real, familiar objects, of plastic models of familiar objects, and of raised line drawings of objects. This result demonstrates that extensive experience in exploring objects at a given spatial location is not required for efficient haptic object recognition. The final experiment pushed further at the limits of our ability to interpret novel inputs from touch. Experiment 3 investigated whether people could use their feet to identify familiar, nameable objects.

After training, the feet can be used for complex motor tasks such as making origami or playing musical instruments—for example, by people born without functioning hands (Jay, 1987). Furthermore, most people use their feet to act on objects such as pedals and balls. However, most people rarely use their feet for shape recognition, and far fewer neural resources are devoted to analyzing inputs from the feet than from the hands. In addition, the structure, flexibility, and proportions of feet are dissimilar to those of hands, so the sensory input from hands versus feet will differ substantially even when feeling the same 3-D shape. People's inexperience at using their feet to recognize objects and the difference between haptic inputs from exploration by foot versus by hand mean that identification of 3-D shapes by the feet might be expected to be extremely poor for untrained participants.

Little research has been conducted on this topic. There is a small literature that covers foot performance measures and laterality effects (Peters, 1988, 1990) and the passive recognition of numbers drawn with a stylus on the toes (Richards & Persinger, 2004), while Peelen and colleagues have investigated the integration of tactile inputs from two fingers from the same or different hands or on two toes from the same or different feet (Peelen, Rogers, Wing, Downing, & Bracewell, 2010). Simple tactile discrimination (passive detection of stimuli applied by an external agent) is possible by the sole of the foot—for example, for spatial position—and tactile perception can even be used to identify 2-D shapes (Courtney & Chow, 2001). Of more relevance to the present experiment is a series of interesting studies by Hajnal and colleagues. They found that the foot can perform as well as the hand at estimating the length of a rod and where it was attached to the limb (Hajnal, Fonseca, Harrison, Kinsella-Shaw, & Carello, 2007; Hajnal, Fonseca, Kinsella-Shaw, et al., 2007). In addition, they found that practice at estimating rod length by wielding it by hand transfers to the foot and vice versa (Stephen & Hajnal, 2011).

However, the only study that I am aware of that has tested object recognition by the feet was conducted by Reed, Caselli, and Farah (1996). They tested familiar, 3-D object recognition by hand and foot with a 65-year-old unilateral tactile agnosic, E.C., and with age-matched controls. E.C. had impaired object recognition for her right hand only. On two testing occasions, she identified 20/40 and 25/40 familiar objects with her right hand, as compared with 36/40 and 37/40 using her left hand. Tactile (passive) perception was also impaired for her right hand (42/54 letters and shapes identified), relative to her left hand (50/54). In contrast, weight, size, length, and texture perception, basic somatosensory function, and general spatial processing all appeared to be intact for E.C.'s right hand. E.C.'s haptic recognition of objects using her right foot (15/25 familiar objects) was similar to that of her left foot (12/25), and 5 age-matched control participants showed similar mean results for their right feet (13/25) and left feet (12/25). Reed et al.'s results indicate that familiar, 3-D object recognition using the feet is possible even without prior training. However, foot recognition was not the main focus of their study, and they tested only 5 elderly control participants and their patient. Crucially, they did not directly compare hand with foot recognition for the same set of objects. Reed et al.'s main finding was that E.C. was impaired at shape perception using her right hand (but not her left hand or her right foot), while basic perceptual processing with her right hand remained intact.

Reed et al. (1996) stated that "given the poor level of normal subjects' performance with foot mediated object recognition it is likely that tactile object recognition is a specialized function of the hand, and therefore not surprising that EC's impairment is apparent primarily in hand mediated object recognition" (p. 887). However, note that Reed et al. reported around 50 % accurate foot recognition, which is far from floor performance. It seems premature to conclude from their results that only the hands are competent at object recognition. In particular, anatomical considerations mean that foot recognition might be harder than hand recognition merely for structural, rather than representational, reasons. For example, the short length of the toes relative to the fingers (see Fig. 5) and the relative inflexibility of the foot make it harder

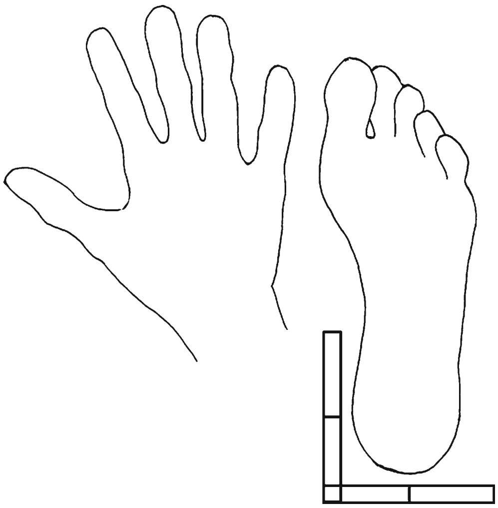

Fig. 5 Outlines of a right hand and right foot scaled to the mean proportions measured for the 32 participants tested in Experiment 3, together with scale bars indicating 1, 5, and 10 cm horizontally and vertically. The foot has a greater overall length, but the hand has much longer digits. Note, too, that the hand has an opposable thumb at an angle to the fingers, whereas the big toe is aligned with the other toes. Together, these differences mean that grasping around an object and picking it up is much easier by hand than by foot

for the foot to pick up or to tightly enclose objects. Thus, gross, global shape information may be harder to extract by foot than by hand. The feet are also probably less able to detect finely detailed shape information. Such anatomical differences also mean that the optimal size and shape of objects for recognition by foot and by hand will likely differ. In Experiment 3, this issue was addressed in two ways. First, a large and varied set of objects was presented (see the Appendix). The objects spanned a wide range of sizes, so the influence of size on hand versus foot object recognition could be investigated. Second, the size of each participant's hand and foot was measured to examine whether this influenced performance.

In Experiment 3, participants tried to name a sequence of 80 familiar objects as quickly as possible in four conditions: using both hands, only the right hand, both feet, or only the right foot (see Fig. 6). Experiment 3 compared the use of one versus both hands or feet in order to test whether any benefit in the use of two hands over one hand would generalize to the use of two feet over one foot. With two-footed exploration, people had to integrate information from a novel combination of inputs, whereas both hands are often used together to feel objects. Any advantage for hand over foot recognition was thus predicted to be stronger when both hands were used versus both feet. People were not allowed to lift the objects, because the aim was to compare performance for the same objects presented in similar conditions and lifting objects is much harder by foot, particularly when using just one foot. Haptic object recognition by hand is efficient even when objects cannot be moved or lifted (Craddock & Lawson 2008, 2009b; Lawson et al., In press), and, in everyday life, objects are often felt by hand without being moved. Thus, this restriction did not make the task unusually difficult for the hands.

Fig. 6 A participant in Experiment 3 as seen from the experimenter's viewpoint. The participant is feeling the wine bottle using both feet. The hands are in their starting positions. The object was placed midway between the hands on hand trials

Method

Participants

Thirty-two right-handed student volunteers from the University of Liverpool took part in the study for course credit (mean age 20 years; 10 were male).

Materials and apparatus

Most of the 80 familiar objects presented were glued onto a CD case or onto a ceramic tile to prevent them from moving as they were being felt. This was not done for the largest objects, such as the desk light. One side of each object was marked. This mark was always aligned with a mark on the table for the hands and on the floor for the feet so that each object was always presented at the same orientation with respect to the hands and the feet. This was important since previous research had shown that object orientation can influence haptic shape processing (Craddock & Lawson, 2008; Lawson, 1999, 2009; Newell et al., 2001).

Except when actively exploring an object, participants were instructed to keep their right and left hands on two small plastic squares at the right and left sides of the table, respectively, and their feet on a low, 7-cm-high bar under the table. Participants sat with the table edge close to their body so that they could not see their feet. A large cloth screen above the table and 20 cm back from its edge blocked their view of their hands. On hand trials, the object was placed between their hands in the center of the table, about 35 cm beyond the front edge of the table (so 15 cm beyond the screen). They moved one or both of their hands inward to explore the object. On foot trials, the object was placed between and in front of their feet, directly under where objects were placed on hand trials. They moved one or both of their feet forward to explore the object when instructed. The table surface was 71 cm above the floor.

Design

The 80 experimental objects were presented in one order to half the participants and in the reverse order to the remaining participants. Each successive set of four trials included one of each of the four conditions (exploration by hand vs. by foot and using the right hand/foot only vs. using both hands/feet). The order of conditions within each of these sets of four trials was varied pseudorandomly. The assignment of objects to the four conditions was counterbalanced in a Latin square design, and 4 of the 16 participants doing each of the two object orders were assigned to each of these four counterbalancing conditions.

Procedure

Participants removed their shoes and socks so that their feet were bare. At the start of each trial, the experimenter told the participant what condition would follow, saying "right hand," "both hands," "right foot," or "both feet." On hand trials, the experimenter then placed the object on the table in front of the participants, in between their hands and at the marked orientation. On foot trials, the experimenter placed the object under the table, in front of their feet, at the marked orientation. The experimenter then pressed a key on the computer keyboard to trigger an auditory signal, "go now," which told the participants that they could start to move either their hands or their feet from their resting position to touch the stimulus. Participants were told not to rotate, move, or try to pick up the objects. They had unlimited time to name each object. They were instructed to respond accurately as their main priority but also to name objects as rapidly as possible and to guess if necessary. As soon as the participants had responded, the experimenter pressed the computer mouse. The computer recorded the interval from the "go now" signal to this time as the participants' RT to name the object. The experimenter then typed in the participants' response whilst the participants returned their hands or feet to the resting position.

The 80 experimental trials were preceded by 6 practice trials, which used a different set of objects. Feedback was provided on the practice trials (but not the experimental trials) by telling participants if they were correct and, if not, by telling them the name of the object that they had just felt. After completing the naming task, people were asked whether they had seen any of the stimuli. The width and length of the participants' right hand and right foot were then measured by the experimenter, together with the length of the middle finger of their right hand and the second toe of their right foot. Finally, a tracing was made around their right hand and their right foot. The experiment took around 45 min to complete.

Results

No participant was replaced. One person said that she had seen part of one object, the racquet, so this trial was removed from the data. Correct responses under 2.2 s or over 35 s were removed as outliers from the RT analyses (fewer than 1 % of trials). ANOVAs were conducted on the mean correct RTs and on the percentages of errors (see Fig. 7). There were no empty cells in the by-participants RT analyses, but there were eight empty cells in the by-items RT analyses. These eight cells were replaced by the mean for the appropriate condition. There were two within-subjects and within-items factors of *body part* (hand vs. foot) and *right-or-both* (right hand/foot vs. both hands/feet).

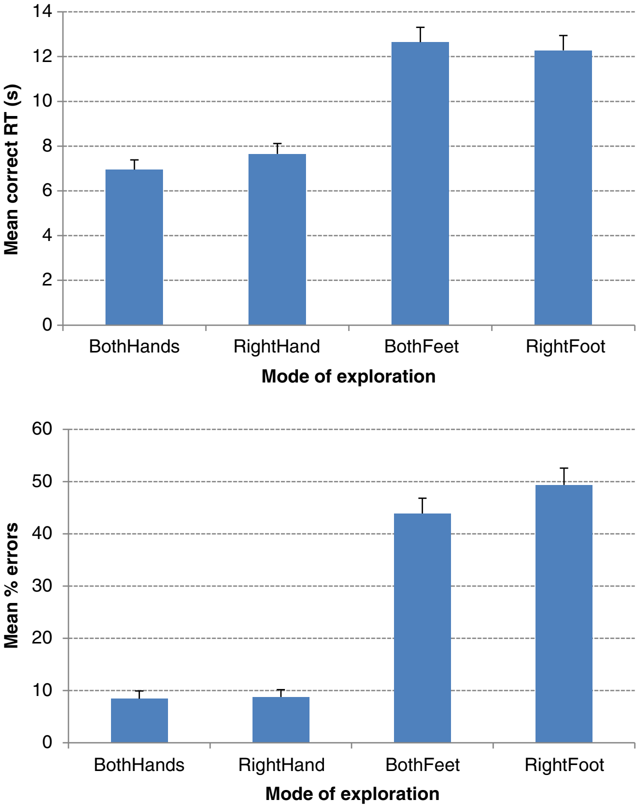

Fig. 7 Mean correct RTs (in seconds) (*top*) and percentages of errors (*bottom*) in Experiment 3 for hand versus foot recognition using only the right hand or right foot or using both hands or both feet. Error bars show 1 standard error of the mean

Much the strongest effect was for body part, which was significant for both RTs, $F_p(1, 31) = 126.154, p < .001$, partial $\eta^2 = .80$; $F_i(1, 79) = 221.345, p < .001$, partial $\eta^2 = .74$, and errors, $F_p(1, 31) = 221.034, p < .001$, partial $\eta^2 = .88$; $F_i(1, 79) = 204.878, p < .001$, partial $\eta^2 = .72$. Hands were faster (7.3 s) and much more accurate (8.6 % errors) than feet (12.5 s, 46.6 %) for recognizing objects. This difference was ubiquitous: All 32 participants were faster and equally or more accurate at hand, as compared with foot, recognition. Only 2/80 objects were faster to be named by foot than by hand (toothpaste tube, shoe), and only 2/80 objects were identified more accurately by foot (scrubbing brush, whisk). Nevertheless, recognition using the feet could be quite fast (participant's mean RTs ranged from 6.7 to 21.3 s) and quite accurate (with 17.5 %–80 % errors).

There was only a weak influence of right-or-both. This was significant for RTs for items only, $F_p(1, 31) = 0.360, p = .5$, partial $\eta^2 = .01$; $F_i(1, 79) = 6.035, p = .016$, partial $\eta^2 = .07$, and it was marginally significant for errors, $F_p(1, 31) = 2.857$,

$p = .1$, partial $\eta^2 = .08$; $F_i(1, 79) = 3.389$, $p = .07$, partial $\eta^2 = .04$. People tended to be faster and more accurate when using both hands or both feet (9.8 s, 26.2 % errors) than when using only their right hand or right foot (10.0 s, 29.1 % errors). However, any advantage was modest at best.

The body part × right-or-both interaction was not significant, although there were marginally significant effects for both RTs, $F_p(1, 31) = 3.683$, $p = .06$, partial $\eta^2 = .11$; $F_i(1, 79) = 0.007$, $p = .9$, partial $\eta^2 = .00$, and errors, $F_p(1, 31) = 3.131$, $p = .09$, partial $\eta^2 = .09$; $F_i(1, 79) = 3.628$, $p = .06$, partial $\eta^2 = .04$. There was a trend for recognition to be faster with both hands (7.0 s, 8.4 % errors) than with the right hand only (7.7 s, 8.8 %), and there was also a trend for recognition to be more accurate with both feet (12.7 s, 43.9 % errors) than with the right foot only (12.3 s, 49.4 %). As for the main effect of right-or-both, these differences were rather small.

Correlations between hand and foot recognition

There was a significant positive correlation between people's RTs to recognize objects using their right hand and their right foot, $r = +.58$, $n = 32$, $p < .001$, and also between them using both hands versus both feet, $r = +.60$, $n = 32$, $p < .001$. There were also positive correlations for errors (for the right hand and right foot, $r = +.40$, $n = 32$, $p = .02$; for both hands and both feet, $r = +.25$, $n = 32$, $p = .17$). Thus, individual participants performed quite similarly whether using their hands or their feet to recognize objects.

Likewise, for a given object, there was a positive correlation for RTs to identify it between using the right hand versus the right foot, $r = +.35$, $n = 80$, $p = .001$, and between using both hands versus both feet, $r = +.33$, $n = 80$, $p = .003$, with similar positive correlations for errors, $r = +.26$, $n = 80$, $p = .02$, and $r = +.32$, $n = 80$, $p = .004$, respectively. Thus, the ease of identifying a given object was similar whether exploration involved the hands or the feet.

Influence of object size

Small items were generally harder to identify by foot (see the Appendix). There was a clear negative correlation between foot recognition errors and the sum of the object's width (W), length (L), and height (H), $r = -.44$, $n = 80$, $p < .001$. Foot recognition was least accurate for the 20 smallest W + L + H objects (60 % errors). There were 51 % errors for the next 20 smallest items, 43 % for the next 20 items, and only 32 % errors for the 20 largest W + L + H items.

Importantly, size did not have this influence on identification by hand (see the Appendix). There was no significant correlation between hand recognition errors and an object's W + L + H, $r = +.08$, $n = 80$, $p = .5$. Hand recognition errors were 5 %, 8 %, 13 %, and 9 % for the smallest to the largest sets of 20 items. This provides evidence against the alternative hypothesis that the effect of size on foot accuracy was simply due to the larger objects being easier to identify per se and suggests, instead, that relative to the hands, the feet are particularly impaired at extracting small-scale shape information.

Although difficulty in acquiring information about smaller items appears to be important in explaining why recognition accuracy is much worse for feet than for hands, object size had little influence on exploration speed. There was no significant correlation between foot recognition speed and W + L + H, $r = +.02$, while hand recognition was somewhat faster for smaller items, with a positive correlation to W + L + H, $r = +.23$, $n = 80$, $p = .04$. Mean hand recognition RTs were 6.9, 7.2, 7.5, and 8.2 s for the smallest to the largest sets of 20 items.

Hand and foot size

The overall hand and foot measurements suggested why object exploration was much easier using hands than using feet (see Fig. 5). The average length of the middle finger was 8 cm tip to base, and its length as a proportion of the length of the palm (base of middle finger to wrist crease) was .82. In contrast, the second toe (tip to base) was only half that length (4 cm), and its length as a proportion of the length of the rest of the foot (base of second toe to heel) was just .21. Finally, the mean maximum span between the thumb and the little finger was twice as large (19.8 cm) as the maximum span from the big to the little toe (9.7 cm). The relatively long length of the fingers, the opposable thumb, and the wide span of the digits mean that hands are much better suited for exploring and, in particular, for grasping around an object.

Given the substantial effect of object size on foot (but not hand) recognition accuracy described in the Influence of Object Size section, we might also expect that the size of people's feet (but not their hands) would influence their accuracy at naming objects. However, there was no significant correlation between recognition accuracy and any of the anatomical measurements taken. This was probably due to the restricted range of hand and foot sizes of our participants. None of the anatomical measurements varied by more than one third across the 32 participants, whereas width, length, and height dimensions varied many-fold across the 80 objects (see the Appendix).

Practice effects on foot recognition

The 80 objects were all presented in the same order for half the participants and in the reverse order for the remaining participants. Recognition of a given object was compared across these two groups of participants. This indicated that there was, at most, only a mild improvement in foot recognition accuracy with practice at the task. There were 10 % more foot naming errors when objects were presented early in the experiment (in the first 10 items, as compared with the final 10 items). Similarly, there were 9 % more errors for the second set of 10 items, as compared with the next-to-last set of 10 items. There were no such effects for the analogous comparisons with the middle 40 items (−1 % and −1 %). The equivalent results for hand recognition accuracy showed no systematic pattern (6 %, −4 %, 6 %, −4 %). Similarly, there were no strong effects or clear trends for RTs, either for feet (20, −430, −595, and 982 ms) or for hands (228, −56, 175, and 803 ms). These results show that people were quite good at using their feet to extract complex 3-D shape information right from the start of testing.

Discussion

Recognition by hand in Experiment 3 (7- to 8-s RTs, 8 %–9 % errors) was similar to that reported for other studies that presented familiar 3-D objects that could not be moved or lifted (with a range of 2–6 s for RTs and 4 %–12 % for errors in Experiment 1 here; Craddock & Lawson, 2008, 2009b; Klatzky et al., 1993; Lawson, 2009, 2011; Lawson et al., In press). In contrast, recognition by foot was clearly much worse, particularly for accuracy (12–13 s for RTs, 44 %–49 % for errors). However, a more detailed analysis suggests that a substantial portion of this disadvantage arises from simple anatomical differences between the feet and hands, rather than from an intrinsic difficulty in representing and interpreting input from the feet. In particular, feet are relatively large, have short digits, and lack an equivalent to the opposable thumb (see Fig. 5). This means that detailed exploration of objects is harder by foot than by hand, especially for small objects. Evidence for this came from the influence of object size on performance. Size had little effect on hand recognition, whereas foot recognition errors doubled from the largest quarter of the objects to the smallest (32 % as compared with 60 %).

Of the six haptic exploratory procedures described by Lederman and Klatzky (1987), enclosure and unsupported holding (which was not permitted in Experiment 3) are likely to be particularly difficult for the feet, while a lack of fine motor control could also make contour following difficult. Enclosure is important for providing global shape information, while contour following is informative about detailed shape, so any difficulty for the feet in using these two exploratory procedures would make 3-D shape recognition hard. Despite these issues, people could use their feet to recognize many familiar objects quite quickly even though they would have had little experience at this task in their everyday lives. Furthermore, there was little effect of practice within the experiment, suggesting that this novel task could be achieved quite successfully with little or no training. Thus, the feet can readily be used to acquire 3-D shape information, which can then be successfully matched to stored object representations acquired through vision and/or feeling objects by hand. An interesting extension of this study would be to examine how the exploratory procedures used by the hand and feet differ during haptic object recognition and whether all differences can be accounted for merely by anatomical constraints for the feet.

The relative ability of the feet to recognize objects is best assessed by contrasting it to object recognition by hand under varying conditions. The studies described below used a variety of methods and stimuli, so direct comparisons with the results of Experiment 3 are not possible, but they do indicate the level of disruption caused by different interventions. Relative to bare-handed exploration (2–8 s for RTs, 4 %–12 % for errors, as described above), haptic object recognition remains accurate—albeit much slower—when only a single finger is used for exploration (31 s, 8 % errors; Lederman & Klatzky, 2004) or when people wear gloves (16 s, 7 % errors; Klatzky et al., 1993). Indeed, even a single gloved finger is quite accurate, although very slow, at object recognition (45 s, 26 % errors; Klatzky et al., 1993).

In contrast, recognition is much harder using only probes held like a pen to touch the object (39 s, 94 % errors reported by Lawson & Bracken, 2011, for two probes with plastic models of objects; 85 s, 60 % errors reported by Lederman & Klatzky, 2004, for one probe with real objects; see also Bholat, Haluck, Murray, Gorman, & Krummel, 1999; Greenwald & Cao, 2012). Lederman and Klatzky (2004) reported similarly poor performance for recognition with a 1.5-mm-thick finger sheath (83 s, 58 % errors) as for a 15-cm-long hand-held probe. The latter finding suggests that there was not difficulty with probes merely because the hand was farther from the object's surface, as compared with when an object is explored with bare skin.

A notable exception to our skillful use of touch when using our bare hands is our slow and inaccurate identification of 2-D raised line drawings (Experiment 2 here; see also Kennedy & Bai 2002; Klatzky & Lederman, 2011; Klatzky et al., 1993; Lawson & Bracken, 2011; Scocchia et al., 2009; Wijntjes, van Lienen, Verstijnen, & Kappers, 2008a, b). Here, error rates are often well over 50 %, while RTs over 60 s are common (although note that, as compared with the stimuli traditionally used, which have lines raised only around 1 mm, RTs for drawings with more salient, higher lines are shorter—12 s in Experiment 2 here; 10 s in Lawson & Bracken, 2011; see Lawson, 2013). The problem in identifying line drawings seems to be mainly due to the lack of depth information per se, rather than the lack of other information about the depicted object, such as its size or the material that it is made of (Lawson & Bracken, 2011). The difficulty of haptic object recognition when probes or rigid finger sheaths are used may also be due to 3-D depth information being reduced or eliminated (Klatzky & Lederman, 2011), since, unlike vision, haptic perception is highly reliant on depth cues (Lawson & Bracken, 2011).

Recognition in Experiment 3 using both feet (13 s, 44 % errors) was less accurate than direct recognition by hand, whether bare-skinned, gloved, or single-fingered. However, it was generally more accurate than bare-handed recognition of 2-D drawings, and it was both faster and more accurate than indirect hand recognition, whether using probes or a finger with a rigid sheath. Therefore, contrary to Reed et al.'s (1996) proposal, it seems that haptic object recognition is not a "specialized function of the hand" (p. 887) but, instead, that the feet are reasonably competent at identifying familiar 3-D objects. In addition, there were substantial correlations between an individual's ability to use their hands and their feet to recognize objects and between hand and foot recognition of different objects. Together, these results support the claim that foot recognition benefits from efficiently accessing a visuo-haptic processing system, which normally analyzes inputs from seeing objects and/or feeling them by hand.

We found little improvement in recognition for two-handed or two-footed relative to one-handed or one-footed exploration in within-subjects comparisons. The two-handed advantage was even weaker than that reported by Craddock and Lawson (2009a), who found that the naming of real, familiar objects was marginally slower and significantly less accurate with one-handed (4.2 s, 9 % errors) than with two-handed (3.8 s, 3 %) exploration in a between-subjects comparison. It is also consistent with the report of Wijntjes et al. (2008b) of 10 % fewer naming errors for two-handed, as compared with one-handed, exploration of raised-line drawings. Together, these results show that haptic object recognition gains, but often by not much, from using both hands or both feet, as compared with just one hand or one foot, for exploration. This is the case even though we have had a lifetime of experience in using both hands together to explore 3-D objects.

General discussion

The present experiments have established that our sense of touch can be used to explore and identify 3-D objects across a wide variety of novel inputs and with no need for lengthy training. Experiments 1 and 2 established that people can use their hands to identify familiar objects felt behind their back just as effectively as objects placed in their normal front position. Experiment 3 found that the recognition of familiar objects by foot was surprisingly good, especially for larger objects. It was much slower and less accurate than recognition by hand, but it was better than recognition using hand-held probes or rigid finger sheaths. This suggests that, relative to indirect exploration using the hand, 3-D shape information acquired by foot was relatively easy to match to stored object representations. Prior experience (either of a spatial location or of using a given body part as an effector) was thus not necessary for haptic object recognition. Indeed, given that we rarely explore the whole of large objects by touch, our stored perceptual representations of items, such as the coat hanger, desk lamp, and kettle, will be largely based on visually acquired information. Thus, people's recognition of objects behind their back or by foot required not only transfer of haptic processing to analyze inputs from an untrained location or an untrained effector, but also mapping between information extracted by different modalities—namely, vision and touch. These results indicate that effective haptic processing does not require long-term (or even short-term) training with combined visual and haptic inputs in order to learn specific spatial mappings. Instead, stored object representations can be accessed readily from novel spatial locations or by untrained body parts.

The present findings have important practical implications for the design of sensory substitution devices (Wall & Brewster, 2006)—for example, for use by the visually impaired (Reich, Maidenbaum, & Amedi, 2012; Schwerdt, Tapson, & Etienne-Cummings, 2009), by amputees (Panerese, Edin, Vecchi, Carrozza, & Johansson, 2009), or by surgeons (Greenwald & Cao, 2012)—and also for the development of novel means of providing information (for example, while driving; Chang, Hwang, & Ji, 2011). The results found here show that people can readily interpret 3-D shape information from unusual spatial locations and from untrained body surfaces. Given that this ability required little training, it suggests that haptic sensory substitution devices hold considerable promise.

These results are consistent with claims that a supramodal or crossmodal object recognition system subserves both visual and haptic identification (Allen & Humphreys, 2009; Amedi et al., 2010; Lacey et al., 2009; Ricciardi & Pietrini, 2011) and extends it to include haptic inputs from invisible locations (behind the back) and to the feet as well as the hands. What remains an open question is the nature of the stored shape representations subserving haptic object recognition. Work has begun on this topic, but there is as yet no consensus as to the input features for haptic object recognition or on fundamental questions such as whether the shape representations are parts based and whether they involve exemplars or prototypes. For example, Yildirim and Jacobs (2013) used a hand simulator to obtain joint angles during grasping. These angles then served as the haptic input features to their model of multisensory (visual and haptic) object recognition. However, as was discussed above, the extraction of such features might alter significantly when objects are grasped in front versus behind the back, and it seems unlikely that they would be invariant across hand and foot recognition. It thus remains as a challenge to such models to determine whether they can be extended to simulate the present results.

The results reported here complement the findings from studies testing people who have been blind from birth and who have their vision restored during adulthood (Held, 2009; Held et al., 2011). These studies answer the Molyneux question—namely, whether a congenitally blind person could, if they were made to see, distinguish between a sphere and a cube. They found that immediately after the restoration of sight, their 5 participants were near chance at matching visually and haptically presented 3-D novel objects. In contrast, they succeeded at the same task when tested within-modally, whether matching two visually or two haptically presented stimuli. However, within a few days, their participants' crossmodal performance had improved significantly, suggesting that relatively little training is required to map between vision and touch.

The present findings extend a small literature comparing haptic perception across different body regions. For example, Hajnal and colleagues have shown that the feet and hands perform similarly at estimating the length of a rod (Hajnal, Fonseca, Harrison, et al., 2007; Hajnal, Fonseca, Kinsella-Shaw, et al., 2007) and that expertise at this task transfers efficiently between the feet and the hands (Stephen & Hajnal, 2011). In addition, Palatinus, Carello, and Turvey (2011) showed invariance of haptic perception of rod length for stimuli grasped by the hand versus attached to the shoulders. Finally, a few studies have investigated object recognition by mouth. Landt (1976) compared oral shape recognition with unimanual and bimanual haptic object recognition in young adults. Oral recognition was worse than manual recognition, particularly when the teeth could not be used. However, in contrast to the similarity between hand and foot recognition found in Experiment 3, here Landt found no correlation between any of the manual recognition measures and either the speed or the accuracy of oral recognition.

Having established that haptic object recognition using the feet is quite good, a further step will be to test whether this recognition ability generalizes to the use of other body parts that are less similar to the hands. The proportions of analogous parts differ across our hands and feet (see Fig. 5). The upright posture of humans has led to the foot evolving to differ from the hand, in contrast to chimpanzee feet, which are anatomically highly similar to their hands. For example, chimpanzees have opposable big toes, and they are adept at grasping and picking up objects with their feet, whereas human feet, unlike our hands, have arches to support bipedal locomotion. Nevertheless, human hands and feet have a much more homologous structure than do other possible pairings of body parts, such as between our hands and mouths.

Anatomical similarity may have played an important role in Experiment 3 by supporting the mapping from inputs acquired by foot exploration to stored representations of objects that have only been explored by eye or by hand. If so, recognition of the same objects using a body part such as the mouth should be poor. However, unlike the foot, the lips and mouth are often used to explore shapes, and for this reason, the mouth might be expected to be relatively expert at 3-D shape perception. Some work has already been done on haptic perception by the mouth (also termed oral stereognosis; see Jacobs, Bou Serhal, & van Steenberghe, 1998, for a review). However, few 3-D shapes have been tested, and little is known about the relative haptic performance of the hand and the mouth for matched shapes and tasks (but see Topolinski & Pereira, 2012, who used a size estimation task). If object familiarity is important, oral recognition of items that are often explored by the mouth (such as cutlery and food items) may be good. Here, the crucial question would be whether the mouth can efficiently recognize familiar, 3-D objects that are not normally explored orally (such as keys and bulldog clips). The results of the present experiments suggest that 3-D shape information can be extracted efficiently by the haptic system irrespective of training. These findings therefore predict that, within the physical limitations of shape exploration by the mouth, recognition should remain good even for objects that the mouth has never explored.

Acknowledgments This research was supported by a grant from the Experimental Psychology Society. I would also like to thank Lifang Huang and Hannah Johnson for help with testing participants.

Appendix

Table 1 Names of the 80 experimental objects presented in Experiment 3, together with their maximum width (W), length (L), and height (H) in centimeters

Foot	Hand	Object Name	W	L	H
0	0	computer mouse	6	11	3
0	0	welly (rubber boot)	10	26	38
6	0	plate	26	26	2
6	0	stapler	12	3	5
12	0	keyboard	47	17	4
12	0	hairbrush	21	5	3
12	0	bowl	17	17	4
12	0	wine glass	7	7	12
12	0	hammer	37	11	3
12	18	scrubbing brush	22	5	3
12	18	whisk	30	6	6
18	0	book	18	23	4
18	0	paintbrush	26	8	2
18	0	spoon	17	4	2
18	0	teapot	17	9	9
18	6	small hand shovel	42	16	7
25	0	toilet roll	11	11	10
25	0	climbing helmet	25	22	11
25	12	tennis racquet	68	26	3
31	0	mug (cup)	11	8	10

Table 1 (continued)

Foot	Hand	Object Name	W	L	H
31	0	shoe	8	26	7
31	6	saucepan	31	19	8
31	6	bicycle helmet	27	20	12
31	6	flipper	54	22	7
31	12	remote control	17	4	1
31	12	telephone	16	21	6
31	12	jug	9	12	14
31	18	screwdriver	23	3	3
35	13	rolling pin	38	4	4
37	0	umbrella	23	8	4
37	0	sellotape	10	10	2
37	0	scissors	18	6	1
37	0	lamp (anglepoise)	26	17	46
37	0	drinks can	6	6	11
37	0	knife	19	1	0
37	6	kettle	13	20	22
43	0	holepunch	6	10	6
43	0	fan	29	22	2
43	12	can-opener	17	4	3
43	12	sieve	22	11	6
43	25	snorkel	42	13	3
50	0	glasses case	15	6	2
50	0	watch	7	7	4
50	0	coat hanger	43	22	0
50	12	wine bottle	6	6	30
50	12	electric drill	32	18	6
50	18	milk bottle	7	7	24
56	0	headphones	14	14	3
56	0	tap	4	9	7
56	6	basket	17	18	6
56	12	saucepan lid	19	19	3
56	12	jar	7	7	10
56	56	sandal	12	28	7
62	0	fork	19	2	2
62	6	comb	18	3	0
62	6	bulldog clip	6	8	4
62	6	shampoo bottle	7	3	17
62	12	tongs	21	7	3
62	25	flip flop	26	11	4
68	0	toothpaste tube	17	4	3
68	0	toothbrush	19	1	1
68	12	plastic box	10	10	6
68	12	spray can	4	4	19
68	31	bicycle lock	35	26	2
68	37	place mat	20	20	1
68	37	grater	27	10	0
68	37	pine cone	10	10	13
75	12	torch (flashlight)	15	4	4
75	25	golf ball	4	4	4
81	0	plug	5	4	4
81	0	sunglasses	15	4	3
81	0	measuring tape	6	6	2
81	12	soap	8	5	3
81	12	salt cellar	4	4	10
87	0	candle	6	6	16
87	0	lighter	2	8	1
87	6	key	7	2	0
87	18	spanner (wrench)	21	5	0
93	12	padlock	5	7	1
100	25	shell	13	8	4

Note. Dimensions are relative to the marked orientation at which objects were presented to participants. With respect to the viewpoint of the participant, width was left/right distance, length was front/back distance, and height was top/bottom distance. Objects are ordered, first, by average foot naming accuracy across the 32 participants (given in the first column, from 0 % errors for the computer mouse up to 100 % errors for the shell) and, second, by average hand naming accuracy (second column)

References

Allen, H. A., & Humphreys, G. W. (2009). Direct tactile stimulation of dorsal occipito-temporal cortex in a visual agnosic. *Current Biology, 19,* 1044–1049.

Amedi, A., Jacobson, G., Hendler, T., Malach, R., & Zohary, E. (2002). Convergence of visual and tactile shape processing in the human lateral occipital complex. *Cerebral Cortex, 12,* 1202–1212.

Amedi, A., Malach, R., Hendler, T., Peled, S., & Zohary, E. (2001). Visuo-haptic object-related activation in the ventral visual pathway. *Nature Neuroscience, 4,* 324–330.

Amedi, A., Raz, N., Azulay, H., Malach, R., & Zohary, E. (2010). Cortical activity during tactile exploration of objects in blind and sighted humans. *Restorative Neurology and Neuroscience, 28,* 143–156.

Azañón, E., Camacho, K., & Soto-Faraco, S. (2010). Tactile remapping beyond space. *European Journal of Neuroscience, 31,* 1858–1867.

Bholat, O. S., Haluck, R. S., Murray, W. B., Gorman, P. J., & Krummel, T. M. (1999). Tactile feedback is present during minimally invasive surgery. *Journal of the American College of Surgeons, 189,* 349–355.

Bremner, A. J., Mareschal, D., Lloyd-Fox, S., & Spence, C. (2008). Spatial localization of touch in the first year of life: Early influence of a visual spatial code and the development of remapping across changes in limb position. *Journal of Experimental Psychology: General, 137,* 149–162.

Chang, W., Hwang, W., & Ji, Y. G. (2011). Haptic seat interfaces for driver information and warning systems. *International Journal of Human-Computer Interaction, 27,* 1119–1132.

Collignon, O., Charbonneau, G., Lassonde, M., & Lepore, F. (2009). Early visual deprivation alters multisensory processing in peripersonal space. *Neuropsychologia, 47,* 3236–3243.

Courtney, A. J., & Chow, H. M. (2001). A study of the discriminability of shape symbols by the foot. *Ergonomics, 44,* 328–338.

Craddock, M., & Lawson, R. (2008). Repetition priming and the haptic recognition of familiar and novel objects. *Perception and Psychophysics, 70,* 1350–1365.

Craddock, M., & Lawson, R. (2009a). Do left and right matter for haptic recognition of familiar objects? *Perception, 38,* 1355–1376.

Craddock, M., & Lawson, R. (2009b). The effects of size changes on haptic object recognition. *Attention, Perception, & Psychophysics, 71,* 910–923.

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

Deibert, E., Kraut, M., Kremen, S., & Hart, J. (1999). Neural pathways in tactile object recognition. *Neurology, 52,* 1413–1417.

Easton, R. D., Srinivas, K., & Greene, A. J. (1997). Do vision and haptics share common representations? Implicit and explicit memory within and between modalities. *Journal of Experimental Psychology: Learning, Memory and Cognition, 23,* 153–163.

Ernst, M. O., Lange, C., & Newell, F. N. (2007). Multisensory recognition of actively explored objects. *Canadian Journal of Experimental Psychology, 61,* 242–253.

Gaissert, N., & Wallraven, C. (2012). Categorizing natural objects: A comparison of the visual and the haptic modalities. *Experimental Brain Research, 216,* 123–134.

Gillmeister, H., & Forster, B. (2012). Hands behind your back: Effects of arm posture on tactile attention in the space behind the body. *Experimental Brain Research, 216,* 489–497.

Greenwald, D., & Cao, C. G. L. (2012). Haptic detection of artificial tumors by hand and with a tool in a MIS environment. *IEEE transactions on haptics, 5,* 131–138.

Hajnal, A., Fonseca, S., Harrison, S., Kinsella-Shaw, J., & Carello, C. (2007a). Comparison of dynamic (effortful) touch by hand and foot. *Journal of Motor Behavior, 39,* 82–88.

Hajnal, A., Fonseca, S., Kinsella-Shaw, J., Silva, P., Carello, C., & Turvey, M. T. (2007b). Haptic selective attention by foot and by hand. *Neuroscience Letters, 419,* 5–9.

Heed, T., Backhaus, J., & Roder, B. (2012). Integration of hand and finger location in external spatial coordinates for tactile localization. *Journal of Experimental Psychology: Human Perception and Performance, 38,* 386–401.

Held, R. (2009). Visual-haptic mapping and the origin of cross-modal identity. *Optometry and Vision Science, 86,* 595–598.

Held, R., Ostrovsky, Y., de Gelder, B., Gandhi, T., Ganesh, S., Mathur, U., & Sinha, P. (2011). The newly sighted fail to match seen with felt. *Nature Neuroscience, 14,* 551–553.

Jacobs, R., Bou Serhal, C., & van Steenberghe, D. (1998). Oral stereognosis: A review of the literature. *Clinical Oral Investigations, 2,* 3–10.

James, T. W., Kim, S., & Fisher, J. S. (2007). The neural basis of haptic object processing. *Canadian Journal of Experimental Psychology, 61,* 219–229.

Jay, R. (1987). *Of Learning Pigs and Fireproof Women*. New York: Random House.

Kennedy, J. M., & Bai, J. (2002). Haptic pictures: Fit judgments predict identification, recognition memory, and confidence'. *Perception, 31,* 1013–1026.

Klatzky, R. L., & Lederman, S. J. (2011). Haptic object perception: Spatial dimensionality and relation to vision. *Philosophical Transactions of the Royal Society B, 366,* 3097–3105.

Klatzky, R. L., Lederman, S. J., & Metzger, V. (1985). Identifying objects by touch: An "expert system". *Perception and Psychophysics, 37,* 299–302.

Klatzky, R. L., Loomis, J. M., Lederman, S. J., Wake, H., & Fujita, N. (1993). Haptic identification of objects and their depictions. *Perception and Psychophysics, 54,* 170–178.

Kobor, I., Furedi, L., Kovacs, G., Spence, C., & Vidnyanszky, Z. (2006). Back-to-front: Improved tactile discrimination performance in the space you cannot see. *Neuroscience Letters, 400,* 163–167.

Lacey, S., Peters, A., & Sathian, K. (2007). Cross-modal object recognition is viewpoint-independent. *PLoS ONE* 2, Article No.: e890.

Lacey, S., Tal, N., Amedi, A., & Sathian, K. (2009). A putative model of multisensory object representation. *Brain Topography, 21,* 269–274.

Landt, H. (1976). Oral and manual recognition of forms. Part II. Test results based on the subjects. *Swedish Dental Journal, 69,* 69–77.

Lawson, R. (1999). Achieving visual object constancy over plane rotation and depth rotation. *Acta Psychologica, 102,* 221–245.

Lawson, R. (2009). A comparison of the effects of depth rotation on visual and haptic 3D object recognition. *Journal of Experimental Psychology: Human Perception & Performance, 35,* 911–930.

Lawson, R. (2011). An investigation into the cause of orientation-sensitivity in haptic object recognition. *Seeing and Perceiving, 24,* 293–314.

Lawson, R. (2013). Why are raised line drawings so hard to recognise by touch? *In preparation*.

Lawson, R., Boylan, A. & Edwards, L. (In press). Where you look can influence haptic object recognition. *Attention, Perception and Performance*.

Lawson, R., & Bracken, S. (2011). Haptic object recognition: How important are depth cues and plane orientation? *Perception, 40,* 576–597.

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology, 19,* 342–368.

Lederman, S. J., & Klatzky, R. L. (2004). Haptic identification of common objects: Effects of constraining the manual exploration process. *Perception and Psychophysics, 66,* 618–628.

Lucan, J. N., Foxe, J. J., Gomez-Ramirez, M., Sathian, K., & Molholm, S. (2010). Tactile shape discrimination recruits human lateral occipital complex during early perceptual processing. *Human Brain Mapping, 31,* 1813–1821.

Miquée, A., Xerri, C., Rainville, C., Anton, J. L., Nazarian, B., Roth, M., & Zennou-Azogui, Y. (2008). Neuronal substrates of haptic shape encoding and matching: A functional magnetic resonance imaging study. *Neuroscience, 152,* 29–39.

Newell, F. N., Ernst, M. O., Tjan, B. S., & Bülthoff, H. H. (2001). Viewpoint dependence in visual and haptic object recognition. *Psychological Science, 12,* 37–42.

Norman, J. F., Clayton, A. M., Norman, H. F., & Crabtree, C. E. (2008). Learning to perceive differences in solid shape through vision and touch. *Perception, 37,* 185–196.

Norman, J., Norman, H., Clayton, A., Lianekhammy, J., & Zielke, G. (2004). The visual and haptic perception of natural object shape. *Perception and Psychophysics, 66,* 342–351.

Overvliet, K. E., Azañón, E., & Soto-Faraco, S. (2011). Somatosensory saccades reveal the timing of tactile spatial remapping. *Neuropsychologia, 49,* 3046–3052.

Palatinus, Z., Carello, C., & Turvey, M. T. (2011). Principles of part–whole selective perception by dynamic touch extend to the torso. *Journal of Motor Behavior, 43,* 87–93.

Panerese, A., Edin, B. B., Vecchi, F., Carrozza, M. C., & Johansson, R. S. (2009). Humans can integrate force feedback to toes in their sensorimotor control of a robotic hand. *IEEE transactions on neural systems and rehabilitation engineering, 17,* 560–567.

Peelen, M. V., Rogers, J., Wing, A. M., Downing, P. E., & Bracewell, R. M. (2010). Unitary haptic perception: Integrating moving tactile inputs from anatomically adjacent and non-adjacent digits. *Experimental Brain Research, 204,* 457–464.

Peters, M. (1988). Footedness: Asymmetries in foot preference and skill and neuropsychological assessment of foot movement. *Psychological Bulletin, 103,* 179–192.

Peters, M. (1990). Neuropsychological identification of motor problems: Can we learn something from the feet and legs that hands and arms will not tell us? *Neuropsychological Review, 1,* 165–182.

Phillips, F., Egan, E. J. L., & Perry, B. N. (2009). Perceptual equivalence between vision and touch is complexity dependent. *Acta Psychologica, 132,* 259–266.

Reales, J. M., & Ballesteros, S. (1999). Implicit and explicit memory for visual and haptic objects: Cross-modal priming depends on structural descriptions. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25,* 644–663.

Reed, C. L., Caselli, R. J., & Farah, M. J. (1996). Tactile agnosia: Underlying impairment and implications for normal tactile object recognition. *Brain, 119,* 875–888.

Reich, L., Maidenbaum, S., & Amedi, A. (2012). The brain as a flexible task machine: Implications for visual rehabilitation using non-invasive vs. Invasive approaches. *Current Opinion in Neurology, 25,* 86–95.

Ricciardi, E., & Pietrini, P. (2011). New light from the dark: What blindness can teach us about brain function. *Current Opinion in Neurology, 24,* 357–363.

Richards, P. M., & Persinger, M. A. (2004). Agility, gnosis and graphaesthesia for the toes and fingers in children: Normative data (ages 7-14 years). *International Journal of Neuroscience, 114,* 17–29.

Röder, B., Rosler, F., & Spence, C. (2004). Early vision impairs tactile perception in the blind. *Current Biology, 14*, 121–124.

Sathian, K., & Lacey, S. (2007). Cross-modal involvement of visual cortex in tactile perception. *Spatial Processing in Navigation, Imagery and Perception*, 119–134.

Schicke, T., & Röder, B. (2006). Spatial remapping of touch: Confusion of perceived stimulus order across hand and foot. *Proceedings of the National Academy of Sciences of the United States of America, 103*.

Schwerdt, H. N., Tapson, J., & Etienne-Cummings, R. (2009). A color detection glove with haptic feedback for the visually disabled. 43rd Annual Conference on Information Sciences and Systems, 1, 681–686.

Scocchia, L., Stucchi, N., & Loomis, J. M. (2009). The influence of facing direction on the haptic identification of two-dimensional raised pictures. *Perception, 38,* 606–612.

Stephen, D. G., & Hajnal, A. (2011). Transfer of calibration between hand and foot: Functional equivalence and fractal fluctuations. *Attention, Perception and Psychophysics, 73,* 1302–1328.

Stilla, R., & Sathian, K. (2008). Selective visuo-haptic processing of shape and texture. *Human Brain Mapping, 29,* 1123–1138.

Tal, N., & Amedi, A. (2009). Multisensory visual-tactile object related network in humans: Insights gained using a novel crossmodal adaptation approach. *Experimental Brain Research, 198,* 165–182.

Topolinski, S., & Pereira, P. T. (2012). Mapping the tip of the tongue - deprivation, sensory sensitisation, and oral haptics. *Perception, 41,* 71–92.

Volcic, R., Wijntjes, M. W. A., Kool, E. C., & Kappers, A. M. L. (2010). Cross-modal visuo-haptic mental rotation: Comparing objects between senses. *Experimental Brain Research, 203,* 621–627.

Wall, S. A., & Brewster, S. (2006). Sensory substitution using tactile pin arrays: Human factors, technology and applications. *Signal Processing, 86,* 3674–3695.

Wijntjes, M. W. A., van Lienen, T., Verstijnen, I. M., & Kappers, A. M. L. (2008a). The influence of picture size on recognition and exploratory behaviour in raised-line drawings. *Perception, 37,* 602–614.

Wijntjes, M. W. A., van Lienen, T., Verstijnen, I. M., & Kappers, A. M. L. (2008b). Look what I have felt: Unidentified haptic line drawings are identified after sketching. *Acta Psychologica, 128,* 255–263.

Yamamoto, S., & Kitazawa, S. (2001). Reversal of subjective temporal order due to arm crossing. *Nature Neuroscience, 4,* 759–765.

Yildirim, I., & Jacobs, R. A. (2013). Transfer of object category knowledge across visual and haptic modalities: Experimental and computational studies. *Cognition, 126,* 135–148.

Zhang, M., Weisser, V. D., Stilla, R., Prather, S. C., & Sathian, K. (2004). Multisensory cortical processing of object shape and its relation to mental imagery. *Cognitive Affective & Behavioral Neuroscience, 4,* 251–259.