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Where you look can influence haptic object recognition

Rebecca Lawson · Amy Boylan · Lauren Edwards

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Abstract We investigated whether the relative position of objects and the body would influence haptic recognition. People felt objects on the right or left side of their body midline, using their right hand. Their head was turned towards or away from the object, and they could not see their hands or the object. People were better at naming 2-D raised line drawings and 3-D small-scale models of objects and also real, everyday objects when they looked towards them. However, this head-towards benefit was reliable only when their right hand crossed their body midline to feel objects on their left side. Thus, haptic object recognition was influenced by people's head position, although vision of their hand and the object was blocked. This benefit of turning the head towards the object being explored suggests that proprioceptive and haptic inputs are remapped into an external coordinate system and that this remapping is harder when the body is in an unusual position (with the hand crossing the body midline and the head turned away from the hand). The results indicate that haptic processes align sensory inputs from the hand and head even though either hand-centered or object-centered coordinate systems should suffice for haptic object recognition.

Keywords Haptic · Object · Recognition · Head · Visual · Gaze · Hand

We are remarkably good at recognizing everyday objects using only our hands. Haptics describes our ability to use our sense of touch to actively explore the world, as opposed to tactile processing, whichinvolves passively acquired inputs from touch. People are usually surprised at how easily they can haptically recognize objects. This typically takes just a few seconds and is accurate (Lawson & Bracken, 2011). However, relative to visual object recognition, it is generally slower and/or less accurate (Craddock & Lawson, 2009b). Furthermore, vision usually dominates over haptics in our everyday life. Vision has a larger field of view and greater acuity and allows us to recognize objects at a distance.

When we explore objects haptically, we usually also look at our hands as they touch the object. Haptics thus typically benefits from the simultaneous availability of visual information about what we are feeling. Integration of information from haptics and vision may be aided by looking at our hands as they explore an object, since this may make it easier to align the different spatial coordinate systems that are used to encode inputs from vision and haptics, such as those centered on our head, our eyes, and our hands. As a result, haptic object recognition may be influenced by our body position. In particular, it may be easier to recognize an object if we have turned our head to look towards it. This head-towards advantage may even occur if our body position is task irrelevant—for example, if we are wearing a blindfold so that we cannot see our body or the object. The present experiments investigated whether, when relying on touch alone to recognize objects, people are influenced by the position of the object and their body or by visual inputs, despite these factors having no influence on the information available about object identity.

We are aware of only one experiment that directly investigates these visual and anatomical factors on haptic object recognition (Scocchia, Stucchi, & Loomis, 2009, described below). However, many studies have shown that spatial processing using our sense of touch is influenced by such factors. For example, Volcic, van Rheede, Postma, and Kappers (2008) asked participants to align rods held in their right and left hands. People make large and systematic errors on this haptic orientation matching task. However, Volcic et al. found that these errors were reduced if people could see the room that they were in and if they looked towards one of their hands, even though their hands and the rods were hidden from view (see also Kaas, van Mier, Lataster, Fingal, & Sack, 2007; Newport, Rabb, & Jackson, 2002; Zuidhoek, Visser, Bredero, & Postma, 2004). Other studies have shown that gazing towards a body part facilitates touch at that location even

R. Lawson (✉) · A. Boylan · L. Edwards
School of Psychology, University of Liverpool, Eleanor Rathbone Building, Bedford Street South, Liverpool L69 7ZA, UK
e-mail: rlawson@liv.ac.uk

when the participant does not gain any useful visual input about the touch (Honoré, Bourdeaud'hui, & Sparrow, 1989).

It is also been found that both eccentric gaze (Harrar & Harris, 2009, 2010) and head position (Ho & Spence, 2007) can systematically bias tactile localization. For example, Pritchett and Harris (2011) manipulated both eye and head position. They asked people to turn their head left, ahead, or right relative to their body and to fixate left, ahead, or right relative to their head. Their right forearm, which was in front of them, was then touched. They then recentred their head and eyes and reported the location of the touch relative to a visual reference. Pritchett and Harris found that localization errors were biased towards both head and eye positions, suggesting that both factors influence the remapping of touch from anatomical coordinates into an alternative spatial coordinate system. However, note that both the direction and the size of their head position effects differed relative to those reported by Ho and Spence, and it is, as yet, unclear why these differences occurred.

Although proprioceptive orienting of gaze normally influences the representation of space, Reuschel, Rösler, Henriques, and Fiehler (2012) showed that proprioceptive reaching by the congenitally blind was not influenced by gaze shifts, although the early blind behaved like sighted participants. This suggests that early visual experience is sufficient for information about gaze shifts to be incorporated into spatial updating mechanisms. Similar results have been reported for tactile detection, with worse performance in a crossed hand condition for the sighted, but not for the congenitally blind (Röder, Föcker, Hötting, & Spence, 2008). Again, this suggests that visual experience is necessary to elicit the default use of an external reference frame to represent tactile stimuli.

Success at most of the spatial tasks tested in the studies described above required inputs to be mapped into a coordinate system that is not hand-centered or stimulus-centered. In contrast, such remapping is not normally necessary for the task of haptic object recognition. Indeed, the haptic processes involved in recognition may be largely independent of those involved in more spatial or action-based tasks (Dijkerman & de Haan, 2007; Sedda & Scarpina, 2012). This proposal is similar to the dual-route account of vision that suggests that there are two visual processing routes within the brain that are at least partially independent (Milner & Goodale, 1995, 2008; Ungerleider & Mishkin, 1982; but see Schenk, 2012), with the dorsal stream supporting spatial processing and the real-time control of action and the ventral stream processing object information for recognition and memory. These two processing streams often require inputs to be represented using different coordinate systems (for example, body-centered or environment-centered systems supporting spatial and action processing versus object-centered systems used for recognition). If this distinction is also relevant for haptic processing (Dijkerman & de Haan, 2007; Sedda & Scarpina, 2012), evidence from tasks such as haptic orientation matching and tactile localization may not be informative about the processing involved in haptic object recognition. In particular, haptic object recognition may be subserved by hand-centered or object-centered representations even if evidence from haptic spatial tasks suggest that alternative reference frames are used to represent stimuli (for example, for orientation matching tasks). This, in turn, means that haptic inputs for object recognition tasks need not necessarily be remapped into an external, allocentric coordinate system in order to represent an object's physical position in the world, nor need they be remapped into a different egocentric (for example, head-centered) coordinate system.

Nevertheless, there are reasons to believe that even haptic object recognition may be influenced by anatomical and visual factors. First, although it might not be necessary, objects may usually be represented using external or head- or body-centered coordinate systems, as well as, or instead of, object-centered or hand-centered coordinate systems. In this case, haptic object processing may be influenced by body position or what is visible of the environment. Supporting this hypothesis, the orientation in depth of an object influences its recognition by touch, indicating that haptics does not rely solely on object-centered representations (Craddock & Lawson, 2008; Ernst, Lange, & Newell, 2007; Lacey, Peters, & Sathian, 2007; Lawson, 2009, 2011; Newell, Ernst, Tjan, & Bülthoff, 2001). Furthermore, Craddock and Lawson (2009a) found that priming of haptic object recognition was invariant to the hand initially used for recognition and to the object's orientation relative to the hand, suggesting that priming was not supported by hand-centered representations.

Second, there is clear evidence from imaging studies for 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 (LOC; e.g., Amedi et al., 2001, 2002; Deibert, Kraut, Kremen, & Hart, 1999; James, Kim, & Fisher, 2007; Miquée et al., 2008; Sathian & Lacey, 2007; Tal & Amedi, 2009) and the intraparietal sulcus (IPS; e.g., Stilla & Sathian, 2008; Zhang, Weissser, Stilla, Prather, & Sathian, 2004) seem to be particularly important. This overlap has even led to the proposal that a modality-independent or crossmodal representation supports both visual and haptic object recognition (e.g., Allen & Humphreys, 2009; Amedi, Raz, Azulay, Malach, & Zohary, 2010; Lacey, Tal, Amedi, & Sathian, 2009). This, in turn, would suggest that haptic inputs are remapped into a different egocentric or an allocentric coordinate system.

Although there are thus good grounds for investigating visual and body position effects on haptic object recognition, only Scocchia et al. (2009) appear to have done this. They found that the recognition of raised line pictures of familiar objects was worse if people looked 45° away from the pictures as they felt them (68 % errors) than if they looked towards them (57 % errors). This head-towards benefit occurred despite participants being blindfolded so they could not see either the picture or their right hand as they felt the picture, which was always placed on their left side.

We were surprised by this result, and so we replicated Scocchia et al.'s (2009) study and also tested whether any effects generalized beyond their choice of stimuli. Haptics is ill-suited to identifying raised line drawings, largely due to the lack of useful depth information, so haptic recognition of line drawings is much slower and less accurate than that of real, everyday objects (Lawson & Bracken, 2011). Furthermore, participants usually report using visual imagery to try to identify line drawings haptically (Lederman, Klatzky, Chataway, & Summers, 1990). Indeed, Scocchia et al.'s tentative account of their finding that head direction influenced haptic recognition was that visual imagery was being used and that it was more successful when the head and eyes were directed toward the picture that was being explored haptically. In order to test this explanation, we compared the haptic recognition of 3-D objects and line drawings. Haptics is skilled at processing 3-D objects and so is less likely to rely on a visual recoding, image mediation strategy to identify them (Lederman et al., 1990; see also Amedi et al., 2010). If 3-D haptic object recognition is influenced by head position, it would suggest that this effect is not merely due to the use of an unusual and stimulus-specific visual translation strategy.

Three experiments were conducted in which participants used their right hand to actively explore objects in order to identify them without being able to see either the objects or their hand. Experiment 1 found that both the location of the object being felt and turning the head towards the object influenced the haptic recognition of 2-D raised line drawings and 3-D scale models of objects. Experiment 2 extended the results of Experiment 1 to the naming of real, everyday 3-D objects. Experiment 3 found the same pattern of results as Experiments 1 and 2, but the effects were not significant. A meta-analysis including all three experiments showed that the recognition advantage for turning the head to look towards an object was reliable when the right hand crossed the body midline to feel objects on the left side, but not when the right hand felt objects on the normal, right side of the body.

Experiment 1

In Experiment 1 two separate groups of participants felt 2-D line drawings or 3-D plastic models of the same set of 24 categories of familiar objects (see Fig. 1). Their task was to name the stimuli. Within each group, half the participants felt objects on their right side (the usual side of the body midline for the right hand) and the other half felt objects on their left side (so their right hand crossed their body midline to touch the objects) (see Figs. 2 and 3). The group tested with the right hand crossing the body midline for line drawings directly replicated Scocchia et al. (2009). The three remaining groups tested whether the head-towards benefit generalized to 3-D stimuli and whether it generalized to objects felt by the right hand on the usual, right side of the body.

Three conditions were tested for each of these four groups. In the head-towards condition, participants looked towards the object that they were feeling, and the object was placed at its usual orientation with respect to the hand and the head. In the head-away condition, the head was turned away from both the hand and the object (see Figs. 2 and 3). These were the two conditions tested by Scocchia et al. (2009). Finally, in the head+objectaway condition, the head was turned away, and the object was rotated in the same direction as the head. The object's orientation was thus aligned with the head rather than the hand. We have previously reported that haptic recognition of raised line drawings was not disrupted by plane misorientation (Lawson & Bracken, 2011), although depth rotation does influence 3-D haptic object recognition (Lawson, 2009).[1] Given the reliable costs that plane misorientation, as well as depth rotation, have on visual object recognition (see Lawson, 1999, for a review), the former, surprising finding needs to be replicated, and for 3-D as well as 2-D stimuli. In addition, we reasoned that when spatial coordinate systems are harder to define (such as when the head, as well as the object, is misaligned with the hand), plane misorientation may be more likely to influence performance.

Method

Participants

Seventy-two volunteer students took part in the study (all self-reported as right-handed; 17 were male; mean age was

[1] The distinction between plane and depth rotation is clear for vision. Plane rotation involves rotation of an object in the picture plane and, for this special case alone, the object's features neither appear nor disappear as it rotates. Only the positions of an object's features vary relative to an external coordinate system. However, it is not possible to specify precisely an analogous axis of plane rotation for haptics. The hand can usually feel most sides of an object, so no plane has a special significance for haptics that is equivalent to that of the picture plane for vision (see Lawson & Bracken, 2011). Nevertheless, for flatter, more 2-D stimuli such as raised line drawings, haptic exploration is largely restricted to a unique, privileged plane of exploration. Here, a canonical orientation of the stimulus within that plane can be specified, with the top of the stimulus furthest away from both the body and the wrist of the exploration hand. This approach was taken here. Furthermore, the two orientations tested here differed by a large (90°) rotation. This difference should be sufficient to distinguish a fairly canonical orientation from a clearly misoriented, atypical orientation (compare the top and bottom photographs, respectively, in Fig. 2).

Fig. 1 The 2-D raised line drawings (top) and 3-D scale models (bottom) of the 24 experimental object categories presented in Experiment 1

20 years, range 18–45). Different participants were used in each of the experiments reported here, and participants were not informed about the purpose of the experiment prior to testing. All the experiments received ethical approval from the appropriate Ethics Committee at the University of Liverpool. Informed consent was obtained prior to testing, and debriefing was provided afterward.

Materials and apparatus

Two small-scale representations (a 3-D model and a raised line drawing) of each of 24 familiar objects were printed in plastic using a 3-D printer (see Lawson & Bracken, 2011, for further details). The stimuli were each mounted onto a plastic base (a CD case) which was 14 cm wide × 12 cm high. The 3-D objects were bilaterally symmetrical or nearly so. Their axis of symmetry was oriented to be parallel to the base (see Fig. 1). The line drawings comprised the occluding contour of the 3-D object given an infinite viewing distance and were produced using lines 1–2 mm thick. No internal edges were represented in these outline contour stimuli, and no pictorial conventions were included to suggest perspective. For example, only two of the four legs of the chair were shown.

Participants sat in a normally lit room at a table. There was a curtain above the table that blocked their view of the stimuli. Participants wore a hat with a metal rod pointing horizontally

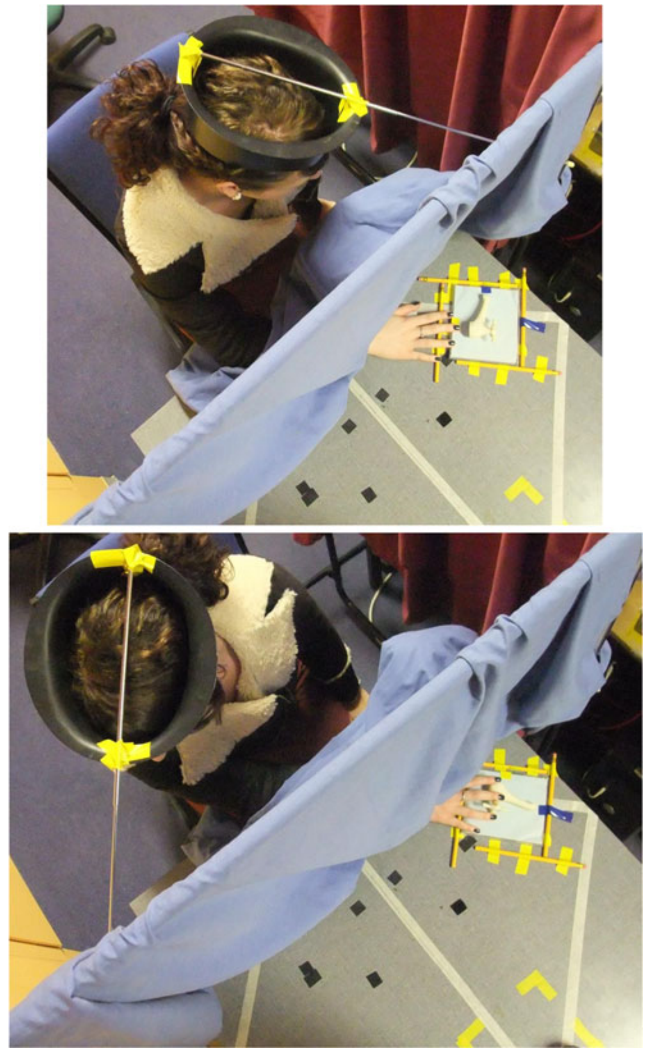


Fig. 2 A participant feeling the 3-D scale model of the tap in the RHandCrosses, HeadTowards condition (top) and the RHandCrosses, Head+ObjectAway condition (bottom) in Experiment 1

forward from it (see Fig. 2). They rested the rod against a vertical bar on the left or right side of the curtain when they were instructed to turn their head left or right, respectively. Participants were instructed to center their body midline with a point on the table marked with tape. The stimuli were placed behind the curtain at one of two marked, 15 × 15 cm locations on the table. The curtain was 20 cm beyond the front edge of the table, and the center of the right and left locations was 10 cm beyond the curtain and 25 cm to the right and to the left of the body midline, respectively. Colored tape on the stimulus base and at the marked locations were aligned to orient stimuli (see Figs. 1 and 2). The starting position for the right hand on right- and left-side trials was indicated by two small, plastic squares that were nearer to both the curtain and the body midline than were the right and left stimulus locations, respectively. Participants rested their right hand on the appropriate starting position square in between each trial.

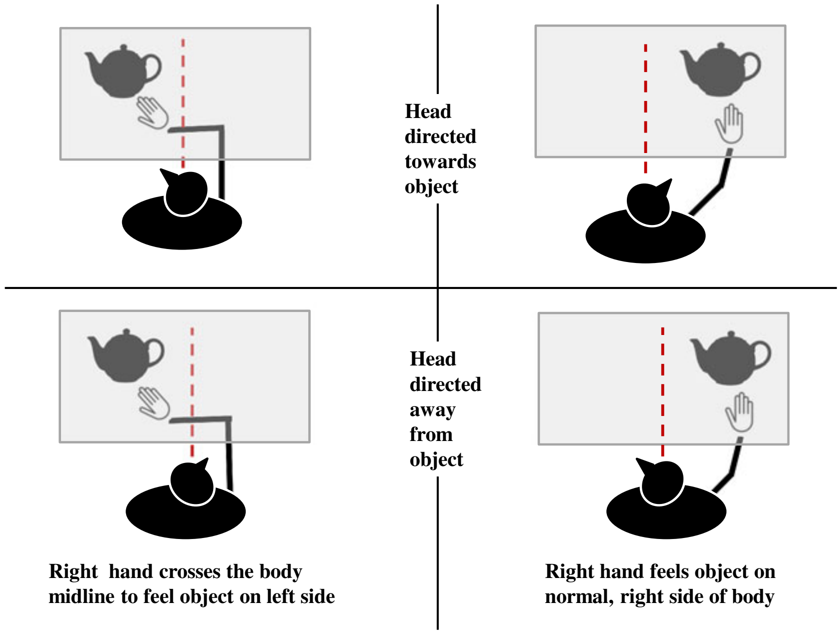


Fig. 3 The four body positions tested in Experiments 1, 2, and 3. The *vertical, red dashed lines* indicate the participant's body midline, which is crossed by the right hand in the right hand left conditions (shown on the left) but not in the normal, right hand right conditions (shown on the right)

Design and procedure

The 24 experimental trials were divided into three blocks of 8 trials, each of which tested a different condition. Half the participants always felt the object on the left side of their body, so their right hand crossed their body midline (see Fig. 3). For this RHandCrosses group, the three conditions were the following: looking left with the object aligned with both the head and the hand (the Head-Towards baseline condition), looking right with the object still aligned with the hand (Head-Away), and looking right with the object aligned with the head (Head+ObjectAway). The remaining 36 participants always felt the object on the right side of their body. For this RHandRight group, their three conditions were the following: looking right with the object aligned with the head and hand (Head-Towards baseline), looking left with the object aligned with the hand (Head-Away) and looking left with the object aligned with the head (Head+ObjectAway).The eight items assigned to each subblock were counterbalanced across participants in a Latin square design. The order of the conditions in the three subblocks was also fully counterbalanced, giving six possible orders. Finally, for the 2 participants assigned to a given group (RHandCrosses or RHandRight) and order of objects and order of conditions, one person felt 2-D line drawings, and the other felt 3-D models. This meant that there were 18 participants in each of the four groups (RHandCrosses or RHandRight) × stimulus type (lines or 3-D) conditions.

Before the start of the experiment, the experimenter described the type of stimuli that people would feel. They were told that the stimuli would be small, plastic models of familiar objects, and they were shown pictures to illustrate the stimuli. The lines group who felt 2-D line drawings were shown a picture of cookie cutters and animal-shaped cookies, and they were told that they would feel something like the cookie cutters. The 3-D group were shown a picture of a 3-D toy duck. The experimental trials were preceded by five practice trials, which were tested in the same condition as the first subblock of experimental trials. At the start of each subblock, the experimenter told the participants to turn their head to face left or right.

On each trial, the experimenter placed the stimulus in the right or left location. Either the stimulus was oriented to be upright relative to the participant's hand (with the bottom of the object nearest to their wrist and the top nearest to their fingertips if the hand reached out naturally to touch the object; see Fig. 2), or it was misoriented by a 90° clockwise rotation for the RHandCrosses group or a 90° counterclockwise rotation for the RHandRight group.[1] The experimenter then pressed a key on the computer keyboard to trigger an auditory "Go" signal, which told the participant that they 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 the stimuli. 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 participant tried to name the object, the experimenter pressed a key on the computer keyboard. The computer recorded the interval from the "Go" signal to this time as the participant's response time (RT) to name the object. The experimenter then typed in the participant's response, while the participant returned their right hand to its resting position. The experiment took around 25 min.

Afterward, people were asked whether they had seen any of the stimuli.

Results

In this and the subsequent experiments, nobody said that they had seen any of the stimuli during the experiment. No participants were replaced in Experiment 1. Correct RTs shorter than 3 s or longer than 60 s were removed as outliers (fewer than 1 % of trials). ANOVAs were conducted on the mean correct RT and on the percentage of errors.[2] There was one within-subjects factor of head (HeadTowards, the head was turned to look towards the object, and the object was oriented normally with respect to the hand; HeadAway, the head was turned to look away from the object, but the object remained normally oriented with respect to the hand; and Head+ObjectAway, the head was turned to look away from the object, and the object was rotated by 90° to be aligned with the head direction but not the hand). There were also two between-subjects factor of stimuli (line drawings or 3-D models) and right hand (RHandCrosses, where the right hand crossed the body midline to feel an object on the left side, or RHandRight, where the right hand felt an object on the normal, right side of the body). Here and in subsequent experiments, unless otherwise stated, all pairwise differences noted below were significant ($p < .05$) in post hoc Newman–Keuls analyses.

Naming in Experiment 1 was a difficult task, particularly for the line drawings, so the main focus of the analysis was on the errors made. Stimuli was significant for both RT, $F(1, 68) = 69.315$, $p = .000$, partial $\eta^2 = .51$, and errors, $F_p(1, 68) = 263.502$, $p = .000$, partial $\eta^2 = .79$. As was expected, line drawings (20.7 s, 60 % errors) were much harder to identify than 3-D models (10.4 s, 21 %). There were no significant interactions involving stimuli.

Most important, there were main effects of head and right hand (marginal for errors), which were modulated by a head × right hand interaction that was marginally significant for RT, $F(2, 136) = 2.502$, $p = .09$, partial $\eta^2 = .04$, and that was significant for errors, $F_p(2, 136) = 4.887$, $p = .009$, partial $\eta^2 = .07$. Post hocs revealed that for the RHandCrosses group (where the right hand crossed the body midline to touch objects), fewer errors were made in the HeadTowards condition (34 %) relative to both the HeadAway (48 %) and the Head+ObjectAway (47 %) conditions, with no difference between these two. In addition, the HeadTowards (14.7 s) and HeadAway (13.8 s) conditions were faster than the Head+ObjectAway (19.7 s) condition. For the RHandRight group (where the right hand felt objects on the usual, right side of the body), there was a trend for fewer errors in the HeadTowards (16.8 s, 36 %) and HeadAway (16.4 s, 37 %) conditions than in the Head+ObjectAway (14.7 s, 42 %) condition. There were no significant differences for RT. The head × right hand × stimuli interaction was not significant for RT, $F(2, 136) = 0.186$, $p = .8$, partial $\eta^2 = .00$, or for errors, $F_p(2, 136) = 0.379$, $p = .7$, partial $\eta^2 = .01$, with the interaction between head position and right-hand position being similar for line drawings and 3-D models (see Fig. 4).

Discussion

Experiment 1 revealed that head direction influenced haptic object recognition. Specifically, people were more likely to recognize both line drawings and 3-D models if they were looking towards, rather than away from, the stimulus. However, this head-towards advantage occurred only when their right hand crossed their body midline to feel an object on their left side. These data extend those of Scocchia et al. (2009). They reported an 11 % advantage for turning the head to look towards a line drawing, but they tested this only when the right hand crossed the body midline to feel the drawing on the left side. We found that when the right hand felt either line drawings or 3-D models on the right side of the body, recognition was no better when the head was directed towards the stimulus than when it was directed away. Here, the hand was on its usual, right side of the body for haptic interactions, which may make it easier to establish spatial coordinate systems to support haptic object recognition.

Importantly, the head-towards benefit when the right hand crossed the body midline was similar for line drawings (14 %), which were like Scocchia et al.'s (2009) stimuli, and for 3-D models (11 % fewer errors). This result suggests that the benefit of proprioceptive orienting of the head is not merely due to improved visual imagery when head direction is aligned with that of the hand, since haptic recognition of 3-D shapes is much less likely to rely on visual imagery than the identification of line drawings (Lederman et al., 1990). Instead, haptic object recognition was influenced by gaze direction even for 3-D objects, provided that there was sufficient misalignment of the different (hand, body, and head-centered) frames of reference.

Experiment 2

The results of Experiment 1 indicated that head direction influenced haptic object recognition but that this effect was modulated by which side of the body the hand felt the object. Experiment 2 had a similar design to Experiment 1 and again

[2] All of the error analyses reported in this article were repeated using arcsine transformed data. This reanalysis produced the same overall pattern of results with just one change to significant effects. This was in Experiment 1 for the post hoc analyses for the RHandRight group only. Here, the difference between the HeadTowards and the other two conditions was a nonsignificant trend for the percentage error analysis, whereas the difference was significant using the arcsine transformed error data.

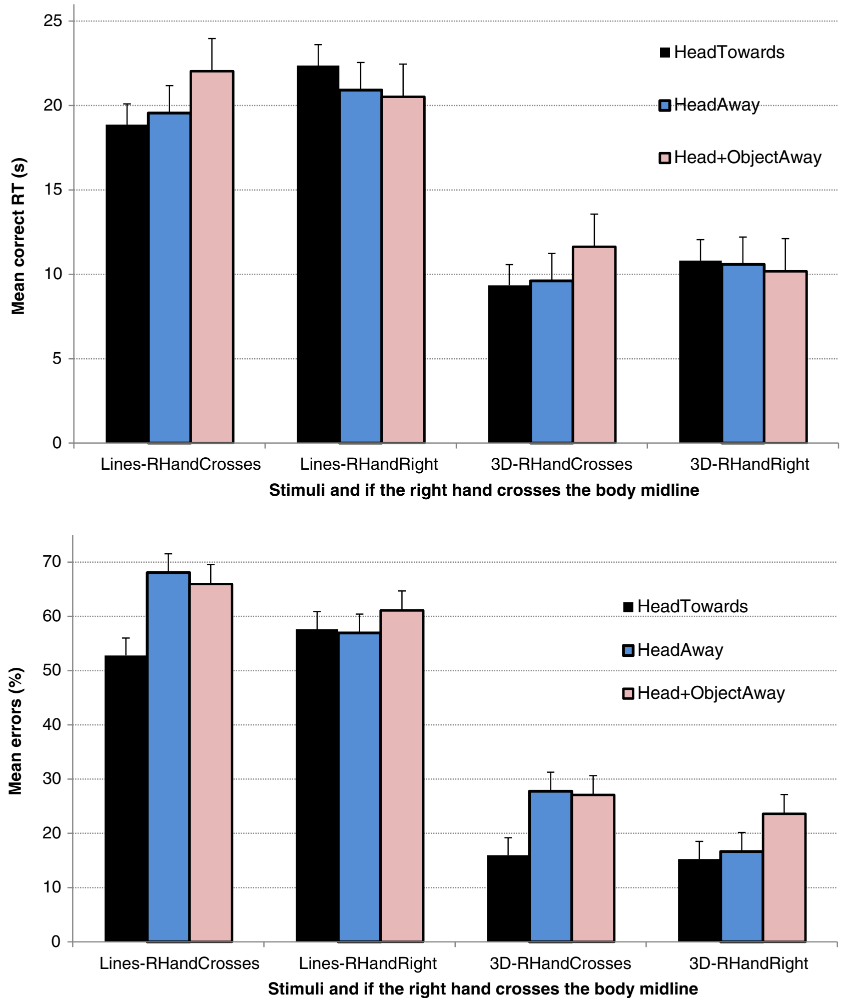


Fig. 4 The mean correct response times (RTs, in seconds; top) and percentages of errors (bottom) in Experiment 1 for the four groups of 18 participants given raised line drawings (Lines) or plastic 3-D scale models (3D) of objects on their left side (so their right hand crossed their body midline to touch the stimuli; RHandCrosses) or their right side (so their right hand felt the stimuli on the normal, right side of their body; RHandRight). The position of the head (directed to look towards the stimulus, HeadTowards, or turned away from it, HeadAway, or turned away with the object aligned with the head, Head+ObjectAway) was manipulated within subjects. Error bars show 1 standard error of the mean

investigated the effects of head direction and object location. However, object location was manipulated within subjects in Experiment 2, and real, everyday objects were presented to test whether proprioceptive orienting of the head influenced haptic object processing under more ecologically valid conditions, using stimuli that had nonshape cues to identity, such as rigidity and heat conductance.

The raised line drawings tested in Experiment 1 were extremely difficult to identify, and the 3-D plastic scale models, although easier to recognize, still took around 10 s to name and had error rates over 15 %. In contrast, haptics is skilled and efficient at processing everyday objects (Klatzky, Lederman, & Metzger, 1985). They can usually be identified haptically around twice as quickly and accurately as 3-D objects defined only by shape (Lawson & Bracken, 2011). Experiment 2 thus tested whether the recognition of objects with full cues to identity (including texture, rigidity, size, and heat conductance, as well as shape) would still be influenced by head direction. Processing most of these nonshape cues should not be influenced by which coordinate system is used to represent the input, unlike the processing of shape information. Thus, any effects of proprioceptive orienting of the head and of the location of the right hand and the object were expected to be weaker to the extent that nonshape cues were used to help to identity the objects. It is important to test the haptic recognition of everyday objects in order to establish whether head and hand position is likely to impact on real-world performance.

Second, Experiment 2 varied the visual information available to participants to investigate whether the effect of head direction found in Experiment 1 was due to its influence on the visual information provided or to proprioception. Experiment 2 tested whether seeing the environment aids haptic identification even if vision provides no information about object identity. In Experiment 1, objects were hidden by a curtain, but people could still see the room that they were in. In Experiment 2, one group wore a mask that allowed some light to enter but blocked all visual information about the environment, while a second group had tunnel vision of the area of the room directly ahead of them. Millar and Al-Attar (2005) similarly varied the information available from vision, while participants haptically learned the locations of landmarks. They found that full, tunnel, and peripheral vision were all better than no vision but that diffuse light vision (with no shape or spatial information) was not. They argued that previous claims that noninformative or task-irrelevant vision benefitted haptic processing (Kennett, Taylor-Clarke, & Haggard, 2001; Newport et al., 2002) were misleading because, in these studies, vision still provided spatial information about the environment—for example, about one's orientation with respect to gravity or one's body position. This could improve performance even if nothing directly related to the task was visible. Millar and Al-Attar's results suggest that spatially informative vision may help haptics but that the mere presence of light does not. This claim was tested in Experiment 2 by comparing haptic object recognition when provided with tunnel vision (which gave some spatial information about the environment) versus masked vision (which only provided diffuse light).

Method

Participants

Sixty-four volunteer students took part in the study (all but two self-reported as right-handed; 11 were male; mean age was 20 years, range 18–39).

Materials and apparatus

A set of 64 familiar objects were presented (see Fig. 5). These were each mounted on a ceramic tile or a plastic CD case, and an arrow on the tile or case indicated the front of the object. The objects were placed at one of two marked locations on a cabinet to the right and left of the participant (see Fig. 6). Objects were oriented so that the arrow always pointed towards the participant so that the front of the object always faced the participant. Participants were told before each trial to turn their head to the right or left and whether the object would be placed on their right or left. They placed their right hand on the near, front corner of the relevant cabinet in preparation for each trial. They kept their left hand on their lap throughout the experiment.

Participants in the TunnelVision group wore a pair of goggles with a 30-cm-long tube attached to the front that provided them with a slot field of view (approximately 30° of visual angle wide by 10° high) directly in front of them. On head-right and head-left trials they fixated a small, circular target that was attached on the right and left walls, respectively. The targets were well above, but in line with, the location of the right and left objects; targets were 157 cm above the floor, while objects were on top of cabinets that were 66 cm above the floor. This ensured that the TunnelVision group did not see their hands or the objects. The mask group wore a mask that blocked their view of the room but allowed some light to enter. They put the mask on before they entered the experimental room so that they had no visual information about the room, and they did not have a target to direct their gaze towards but they were instructed to gaze in the same directions as the TunnelVision group.

Fig. 5 Examples of 13 of the real objects presented in Experiments 2 and 3

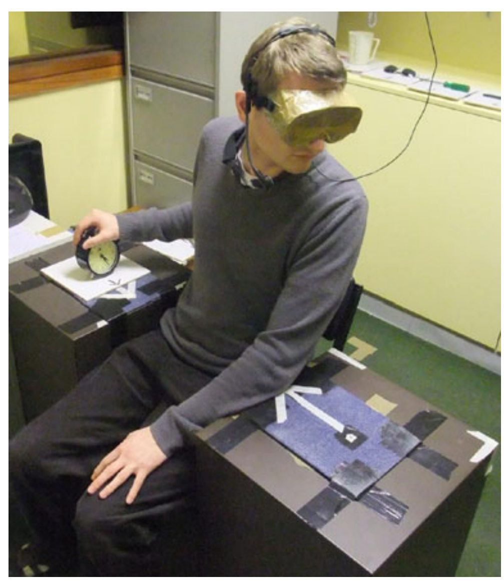


Fig. 6 A photograph of the setup used in Experiment 2 showing the two object locations (left and right of the body midline for the RHandCrosses and the RHandRight conditions, respectively). A masked group participant is feeling the alarm clock on a RHandRight, HeadAway trial

Design and procedure

The objects were divided into four sets. The allocation of the four conditions (right hand to the right or left and head directed to the right or left) to each of these sets was counterbalanced across participants using a Latin square design. The 64 experimental trials were divided into subsets of 4 trials. Within each subset, one 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.

On each trial, the experimenter placed the object in the appropriate location and said to the participant "head right, hand left," for example. 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 recorded from the offset of the double beep using a microphone headset 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 a different set of familiar objects. The experiment took around 45 min to complete.

Results

Four participants who made over 15 % errors were replaced (means of 31 %, 27 %, 22 %, and 18 % errors). 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 RT and on the percentage of errors. There were two within-subjects factors of head (turned towards or away from the object) and right hand (RHandCrosses, where the right hand felt an object on the left side, or RHandRight, where the right hand felt an object on the normal, right side of the body) and one between-subjects factor of vision (the Mask group and the TunnelVision group). There were no significant effects in the error analyses, so these are not reported, but errors are plotted on Fig. 7.

There was a main effect of head (but not of right hand), which was modulated by a significant head × right hand interaction, $F(1, 31) = 5.823$, $p = .02$, partial $\eta^2 = .09$. Post hocs revealed that when the right hand crossed the body midline, people were faster when their heads were turned towards (4,039 ms) rather than away from (4,484 ms) the object. The same trend occurred when the right hand was on the right side; however, the effect was much weaker (only 150 ms faster, rather than 450 ms), and the difference between the head being turned towards (4,129 ms) versus away from (4,284 ms) the object was not significant. Vision was not significant, $F(1, 62) = 0.122$, $p = .7$, partial $\eta^2 = .02$, with similar performance for the Masked (4,275 ms, 7.1 % errors) and TunnelVision (4,193 ms, 8.2 %) groups. No interaction involving vision was significant (all Fs < 1.5).

Discussion

Two main findings from Experiment 2 extended those of Experiment 1 to a different, more ecologically relevant set of stimuli—namely, real, everyday objects. First, turning the head towards an object made it easier to identify by touch even though neither the object nor the hand feeling it was visible. Second, this effect was modulated by the position of the right hand as it felt the object. There was a clear benefit of looking towards the object if the right hand had to cross the body midline to feel the object on the left side. In contrast, there was only a weak trend for this benefit to occur if the right hand felt the object on the usual, right side of the body.

A third result was that varying the visual information available did not influence haptic object recognition: The tunnel vision group were no better than the masked group. This result contrasts to the advantage reported by Millar and Al-Attar (2005) for tunnel vision relative to diffuse vision. However, the tunnel vision group in Experiment 2 could not see their hands or the objects that they were feeling, whereas the tunnel vision group in Millar and Al-Attar's study could see both the stimulus and their hands. It seems likely that this extra, task-relevant information available to Millar and Al-Attar's tunnel vision group explains their advantage over the diffuse vision group. Our result suggests that providing only general visuospatial information about the environment does not benefit haptic object recognition. This, in turn, suggests that the influence of head direction that was found in Experiments 1 and 2 arises from its effects on proprioception, rather than on vision.

Experiment 3

The results of Experiments 1 and 2 indicated that there is an effect of head direction on haptic object recognition but that the effect is found reliably only when the right hand crosses the body midline. A final study was conducted to attempt to determine whether the benefit of turning the head towards the exploring hand occurred only when the right hand crossed the body midline to feel objects on the left side. As in Experiment 2 (but in contrast to Experiment 1), the two critical factors of head direction and right-hand position were manipulated within subjects. In order to increase the size of the stimulus set, people were asked to name both real and 3-D plastic models of objects. Recognition of real objects was expected to be much

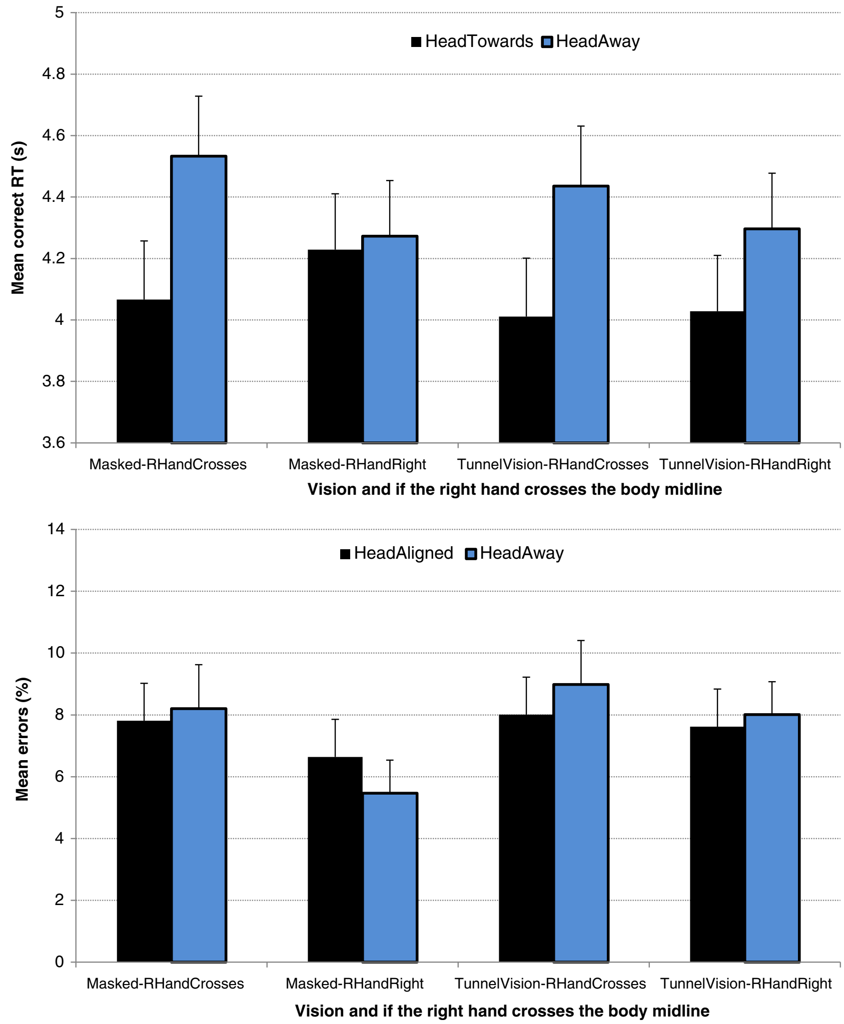


Fig. 7 The mean correct resonse times (RTs, in seconds; top) and percentages of errors (bottom) in Experiment 2 for the masked and the tunnel vision groups when their right hand felt an object on the normal, right side of their body (RHandCrosses) or when their right hand crossed their body midline to feel an object on their left side (RHandRight) and when their head was directed to look towards the object (HeadTowards) or was turned to look away from it (HeadAway). Error bars show 1 standard error of the mean

easier than recognition of the plastic models. Nevertheless, the results of Experiments 1 and 2 suggested that the same pattern of results should be obtained with both types of stimuli.

Method

Participants

Thirty-two volunteer students took part in the study (all self-reported as right-handed; 5 were male; mean age was 21 years, range 18–50).

Materials and apparatus

Two sets of 36 familiar objects were presented, which came from 72 different basic-level categories. One set comprised real, everyday objects, most of which were a subset of the stimuli used in Experiment 2. The other set comprised 3-D plastic printed models, most of which were a subset of the stimuli used in Experiment 1. Each stimulus was mounted on a ceramic tile, a plastic CD case, or a square piece of carpet tile, and an arrow on the mount indicated the front of the object. The objects were placed at one of two marked locations on a table to the right and left of the participant (see Fig. 8). Participants sat with their body midline lined up with a marker on the table, and they placed their right hand on a marker 40 cm to their right or 40 cm to their left in preparation for each trial. The mount of each object was placed such that the corner furthest from the participant was 40 cm to the left or right of the body midline mark and 30 cm away from the edge of the table. Objects were oriented so that the arrow always pointed towards the front of the table so that the front of the object always faced the participant. Participants were told before each trial to turn their head to the right or left, and they

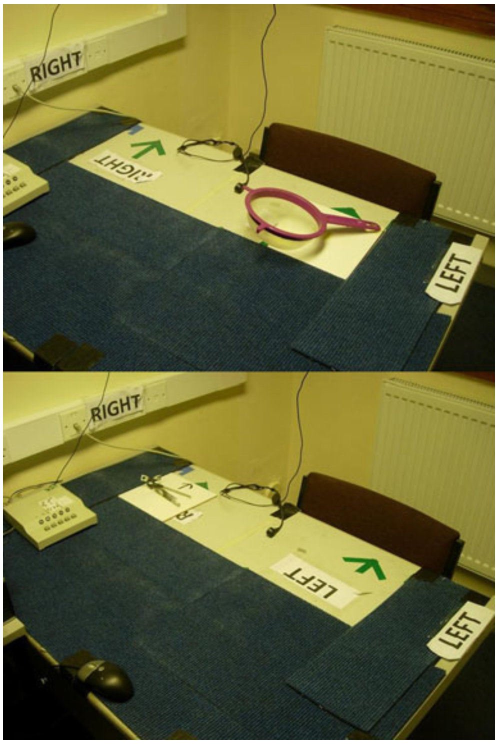


Fig. 8 The experimental setup in Experiment 3 with the sieve in the left position (top; for RHandCrosses conditions) and the can-opener in the right position (bottom; for RHandRight conditions)

were told whether the object would be placed on their right or left. They kept their left hand on their lap throughout the experiment. Participants wore a mask that blocked their view of the room but allowed some light to enter. They put the mask on before they entered the experimental room, so they had no visual information about the room.

Design and procedure

The objects were divided into four sets. The allocation of the four conditions (hand right or left and head right or left) to these sets was counterbalanced across participants using a Latin square design. The 64 experimental trials were divided into subsets of 4 trials. Within each subset, one 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.

On each trial, the experimenter placed the object in the appropriate location and said to the participant "head right, hand left," for example. 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 voice saying "Go," which 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 recorded from the onset of the "Go" signal, using a microphone headset attached to a PC computer. The experimenter recorded trials on which participants made naming or other errors. The experimental trials were preceded by eight practice trials. These presented stimuli that were either real or model objects, depending on which stimulus set would be presented in the first half of the experiment. The practice items came from different categories than the experimental stimuli, and a mixture of the four conditions were presented on the practice trials. The experiment took around 45 min to complete.

Results

No participants were replaced. Correct RTs shorter than 0.75 s or longer than 35 s were removed as outliers (fewer than 1 % of trials). ANOVAs were conducted on the mean correct RTs and on the percentages of errors. There were three within-subjects factors of stimuli (real, everyday objects or 3-D plastic models), head (turned towards or away from the object), and right hand (RHandCrosses, where the right hand felt an object on the left side, or RHandRight, where the right hand felt an object on the normal, right side of the body) and one between-subjects factor of OrderOfStimuli (real objects first or 3-D models first).

Apart from the large difference between the real and the 3-D model objects, none of the predicted effects were significant. For stimuli, real objects (5,322 ms, 7.3 % errors) were much easier to recognize than 3-D models (8,854 ms, 30.4 %) for both RT, $F(1, 30) = 115.340$, $p = .00$, partial $\eta^2 = .79$, and errors, $F(1, 30) = 125.543$, $p = .00$, partial $\eta^2 = .81$. The main effects of head and right hand and the head × right hand interaction were not significant for either RT, $F(1, 30) = 0.064$, $p = .8$, partial $\eta^2 = .00$; $F(1, 30) = 0.843$, $p = .4$, partial $\eta^2 = .03$; and $F(1, 30) = 0.91$, $p = .3$, partial $\eta^2 = .03$, respectively, or for errors, $F(1, 30) = 2.097$, $p = .1$, partial $\eta^2 = .07$; $F(1, 30) = 1.582$, $p = .2$, partial $\eta^2 = .05$; and $F(1, 30) = 2.546$, $p = .1$, partial $\eta^2 = .08$, respectively[3] (see Fig. 9). The only significant interactions were not expected and were for RTs for right hand × order of stimuli, $F(1, 30) = 13.269$, $p = .001$, partial $\eta^2 = .31$, and for errors for stimuli × right hand, $F(1, 30) = 4.221$, $p = .05$, partial $\eta^2 = .12$.

[3] Neither the main effect of head nor the head × right hand interaction was significant for errors in Experiment 3. However, the confidence interval for errors for the advantage of turning the head towards the hand touching an object when the right hand crosses the body midline does not include zero (see Fig. 10c). Both of these results are correct; there was a significant effect of head if only the data for the right hand crossing the body midline condition is included, $F(1, 30) = 6.008$, $p = .02$, partial $\eta^2 = .17$, with fewer errors made when the head looked towards (17.7 %) rather than away from (21.9 %) the hand.

Meta-analysis of experiments 1, 2, and 3

Although Experiment 3 had a similar design to Experiments 1 and 2, the null findings failed to replicate their results, which revealed a significant interaction between head direction and the position of the right hand as it explored an object. Nevertheless, the pattern of results was the same across all three experiments.[3] Meta-analyses were conducted that combined the results for all three experiments in order to assess the strength of evidence for the recognition advantage for turning the head towards an object being felt. The head-towards advantage (the difference between turning the head away from the object minus turning the head towards the object) was calculated separately for RTs and errors when the right hand crossed the body midline to touch objects on the left side and, separately, when the right hand felt objects on the right side of the body (see Fig. 10).[4] The results of these four meta-analyses indicated that the advantage for turning the head towards the exploration hand was small but reliable for both RTs and errors when the right hand crossed the body midline to feel an object on the left side but that there was no equivalent advantage for directing the head towards the object when the right hand felt an object on the normal, right side of the body.

Discussion

The same pattern of results was found in Experiment 3 as in Experiments 1 and 2. However, in contrast to the two previous experiments, here the advantage of turning the head towards the object being explored was not significant for either position of the right hand tested. This was probably due to a combination of the small size of the head-towards benefit and of testing fewer participants in this final study than in the previous two studies, resulting in less power to detect the effect. Importantly, though, the meta-analyses that combined evidence across the three experiments reported here clearly point to a small but consistent head-towards advantage when the right hand crosses the body midline to feel objects on the left side (Fig. 10a, b). In contrast, there was no evidence in the meta-analyses for a head-towards advantage when the right hand felt objects on the normal, right side of the body (Fig. 10c, d).

General discussion

Three experiments were conducted that investigated the influence of anatomical position on the haptic recognition of raised line drawings, 3-D plastic scale models, and real, everyday objects. The results indicated that directing the head to look towards the hand exploring an object improves recognition of that object. However, this effect of proprioceptive orienting was modulated by body posture: It occurred only when the exploration hand crossed the body midline to feel objects in an anatomically unusual location (see Fig. 10). In a separate study, haptic object recognition by the right hand was not found to be disadvantaged when objects were placed to the right side or even behind the participant, relative to when the objects were placed in front (Lawson, 2013). Together these results suggest that haptic object recognition is sensitive to disruption only if the exploration hand crosses the body midline; if the hand is on the normal side of space, its exact position is irrelevant.

Our results argue against Scocchia et al.'s (2009) explanation of the head direction effect as reflecting the use of visual imagery in haptic identification. We found the same pattern of head position effects with 3-D scale models and real, everyday objects as with raised line drawings. This would not be predicted if visual imagery mediated the advantage of looking towards the object being felt, because visual imagery probably plays a much less important role in 3-D object recognition than in the recognition of line drawings (Lederman et al., 1990).

We also investigated whether the nature of the visual information available modulated the head-towards advantage. The same interaction between head direction and body position was found when people could see the room that they were in (Experiment 1 and the tunnel vision conditions in Experiment 2) and when people had no relevant visual information to help them to establish an accurate visuospatial coordinate system (the masked condition in Experiment 2). Furthermore, there was no difference between the masked and tunnel vision conditions in Experiment 2, while another unpublished study also found no overall difference between masked, tunnel vision, and eyes-closed conditions, which were varied within subjects.[4] These results indicate that variation in visual information has little influence on haptic object recognition either in general or, specifically, on the head-towards advantage, provided that the visual input does not provide direct cues to object identity. However, our results also show that the head-towards advantage is rather weak (see Fig. 10), so it would require a much larger scale study to assess this claim thoroughly.

[4] A further, similar experiment was conducted that is not reported here. In this experiment, the right hand always crossed the body midline to feel everyday objects placed on the left side. Head direction (looking towards or away from the right hand) was varied, as was vision. Three visual conditions were tested within subjects: wearing a mask with the eyes closed, wearing a mask with the eyes open, and wearing a tube that permitted tunnel vision of some of the surrounding environment but blocked the view of the right hand and the object. Consistent with the results of the experiments reported here, for the RHandCrossed conditions, people made significantly fewer errors when they looked towards their right hand than when they looked away. There were no significant effects on RT and no significant effect of manipulating visual conditions. When the results of this extra experiment were added to the meta-analyses, the 95 % confidence intervals for the conditions when the right hand crosses the body midline remained above zero for both RTs and errors (see Fig. 10a, b).

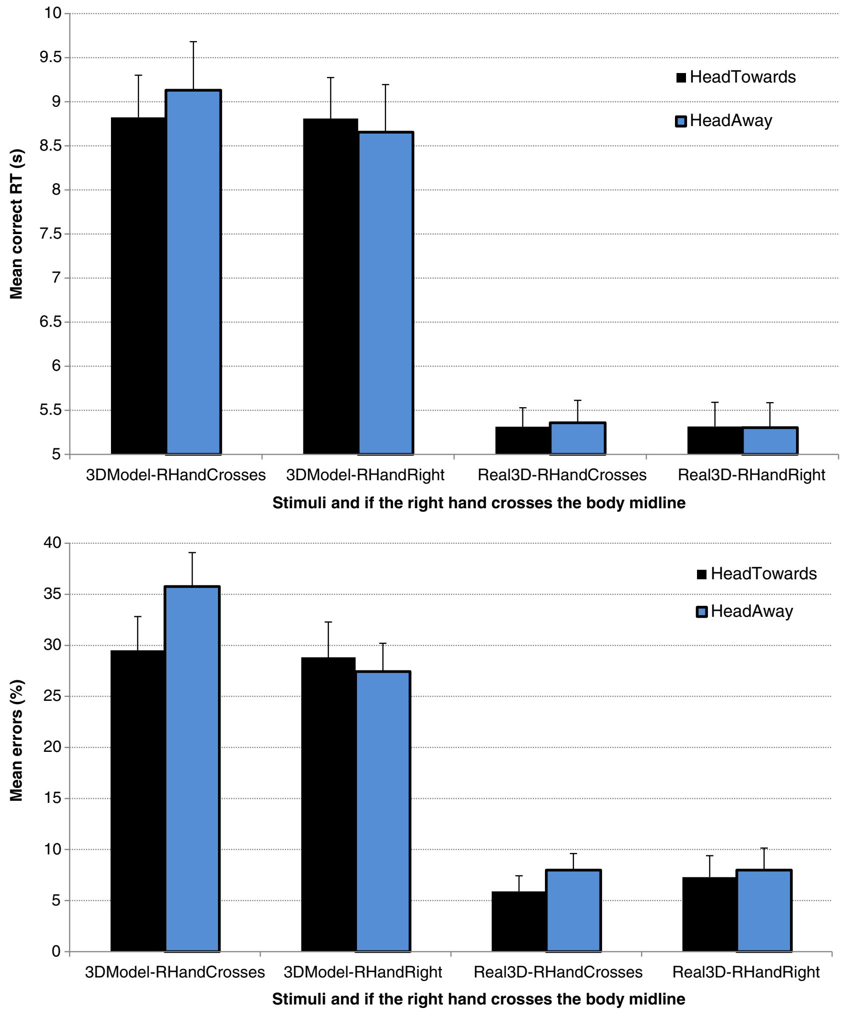
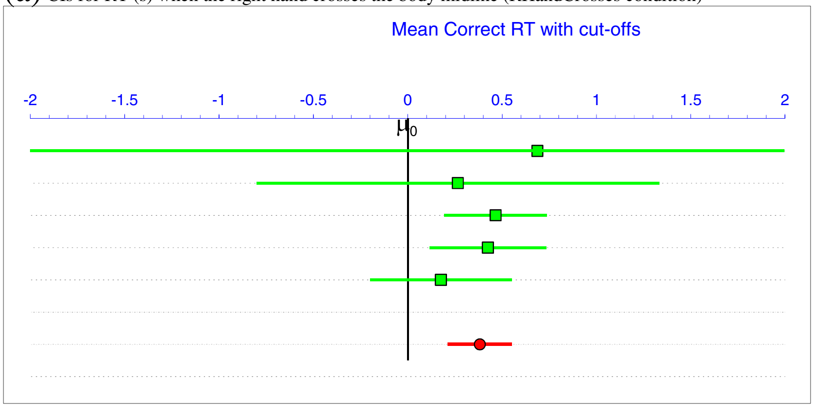


Fig. 9 The mean correct response times (RTs, in seconds; top) and percentage errors (bottom) in Experiment 3 for participants given plastic 3-D scale models (3DModel) of objects and real, everyday objects (Real3D) to identify when their right hand crossed their body midline to feel an object on their left side (RHandCrosses) or when their right hand felt an object on the normal, right side of space (RHandRight) and also when their head was aligned to look towards the object (HeadTowards) or was turned to look away from it (HeadAway). Error bars show 1 standard error of the mean

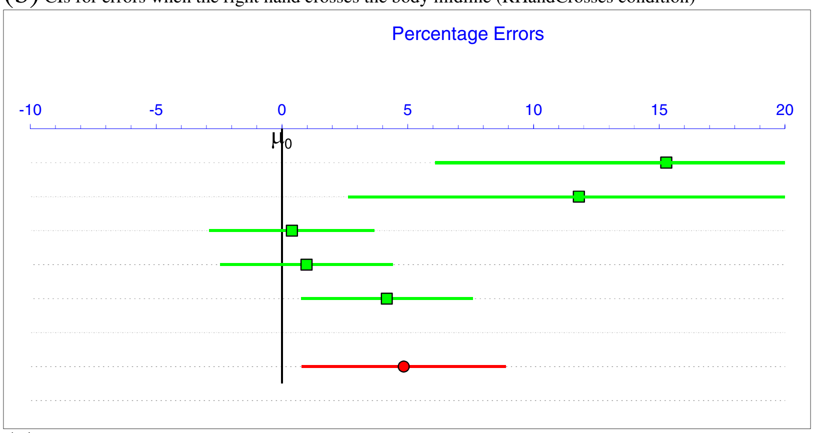
In these experiments, head direction was only coarsely aligned with hand and object location. For example, in Experiment 1, the head was directed at a greater angle from the body midline than the exploration hand and the object (see Fig. 2) while in Experiment 2, the head pointed towards a location above the exploration hand and object. Nevertheless, even this coarse alignment of visual and haptic frames of reference was sufficient to improve haptic object recognition relative to when the head and hand were misaligned by at least 90°. Furthermore, in our experiments, only head direction was monitored, and participants were not told where to fixate their eyes. Nevertheless, gaze direction (which is the combination of head and eye positions) was likely to have been highly correlated with the direction that the head pointed. It remains for future research to try to determine the relative contribution of head and eye direction to the head-towards advantage found here.

Our results show that head direction effects persist even when the spatial component of the task is relatively weak, for the naming of everyday objects. Note, too, that people could not see their arms, their hands, or the objects in any of the experiments reported here. Stronger effects of proprioceptive orienting are likely to occur if people can see their body. This would be analogous to the visual enhancement of touch. Here, vision of a stimulated body part (but not vision of a control, neutral object) improves tactile sensitivity (Forster & Eimer, 2005; Kennett et al., 2001; Taylor-Clarke, Kennett, & Haggard, 2002; but see also Johnson, Burton, & Ro, 2006), even without proprioceptive orienting towards the body part (Tipper et al., 1998) and even for body parts that cannot usually be seen, such as the back of the neck (Tipper et al., 2001). Other results indicate that vision has an important role in specifying perceived anatomical body position, such as the rubber hand illusion (Botvinick & Cohen, 1998) and the

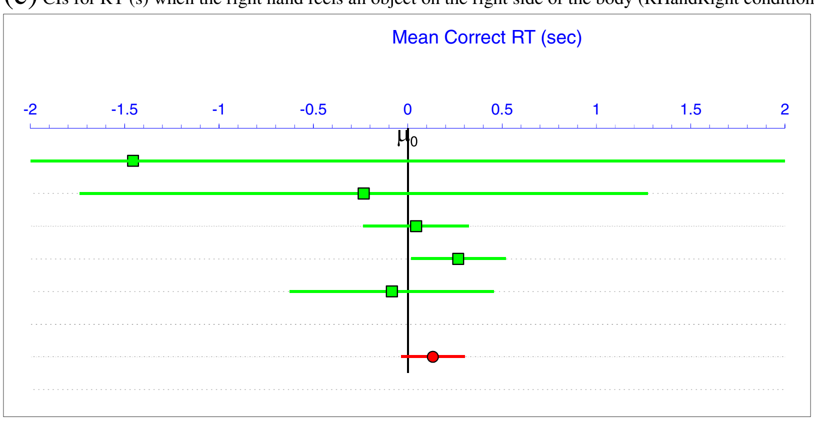
(a) CIs for RT (s) when the right hand crosses the body midline (RHandCrosses condition)



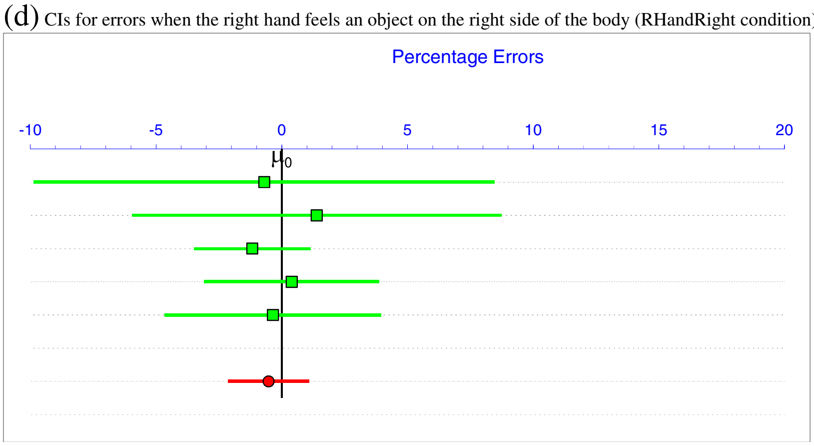
(b) CIs for errors when the right hand crosses the body midline (RHandCrosses condition)



(c) CIs for RT (s) when the right hand feels an object on the right side of the body (RHandRight condition)



(d) CIs for errors when the right hand feels an object on the right side of the body (RHandRight condition)



◀ **Fig. 10** Forest Plots of the between-subjects 95 % confidence intervals (CIs; *green*) showing the magnitude of the advantage of turning the head towards (as opposed to away from) the right hand as it touched objects (the HeadAway − HeadTowards difference). The CIs are plotted individually for the line drawing group and 3-D model group separately in Experiment 1 (the top and second CIs respectively) and for the masked group and the tunnel group separately in Experiment 2 (the third and fourth CIs, respectively) and for Experiment 3 (lowest, *green* CIs). CIs are plotted separately for the RHandCrosses conditions (where the right hand crossed the body midline to touch objects on the left side) and the RHandRight conditions (where the right hand felt objects on the normal, right side of the body). The lowest, *red* CI on each graph shows a random effects model for the meta-analysis including all five groups (Cummings, 2012). The meta-analyses suggest that if your right hand crosses your midline, there is a small but reliable head-towards recognition advantage for both RTs (**a**) and errors (**b**) when the head is directed towards the object that you are feeling. However, there is no analogous head-towards advantage for either RTs (**c**) or errors (**d**) if your right hand feels an object on the normal, right side of the body (see note 3)

finding that seeing a body part can affect estimates of tactile distance (Taylor-Clarke, Jacobsen, & Haggard, 2004).

So far, in this article, we have suggested that when the head is not directed towards the hand exploring an object, haptic recognition is harder because of the misalignment of visual and haptic spatial coordinate systems. An alternative explanation is that, first, spatial attention tends to be allocated to where the head is directed and, second, that haptic recognition improves when spatial attention is directed towards the location of the object being explored. Certainly there is both multimodal and crossmodal evidence supporting the claim that a supramodal system controls spatial attention (e.g., Spence, Pavani, & Driver, 2000; see Macaluso & Maravita, 2010, for a review). This predicts that attracting attention to a spatial location in one modality can modulate processing in another modality at that location. This attentional hypothesis could thus explain the head-towards advantage. However, importantly, this attentional account does not predict that the head-towards advantage should be restricted to the situation when the exploration hand crosses the body midline. Nevertheless, this is what we observed here (see Fig. 10). We therefore believe that our data are best explained in terms of head direction influencing the remapping of hand-centered representations into different spatial coordinate systems, rather than its effects on spatial attention.

In conclusion, the results of our experiments show that head direction can influence haptic object recognition. They are consistent with the head-towards advantage occurring when it is relatively hard to remap between different spatial coordinate systems. The benefit of looking towards the object being explored by the right hand occurred only if the object was placed on the left side of the body, providing evidence against a spatial attentional account. Furthermore, the head-towards advantage occurred for a range of 3-D stimuli, not just line drawings, providing evidence against a visual imagery account. Finally, our findings suggest that the effects due to changes of head direction are not mediated by changes in the visual input. These results instead support the claim that haptic object recognition is achieved by remapping inputs from hand-centered to alternative coordinate systems and that, because of this, a misalignment of different coordinate systems makes haptic recognition harder.

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