Perception, 2011, volume 40, pages 576 – 597

doi:10.1068/p6786

Haptic object recognition: How important are depth cues and plane orientation?

Rebecca Lawson, Sarah Bracken
School of Psychology, University of Liverpool, Eleanor Rathbone Building, Bedford Street South, Liverpool L69 7ZA, UK; e-mail: rlawson@liverpool.ac.uk
Received 30 July 2010, in revised form 5 May 2011; published online 6 July 2011

Abstract. Raised-line drawings of familiar objects are very difficult to identify with active touch only. In contrast, haptically explored real 3-D objects are usually recognised efficiently, albeit slower and less accurately than with vision. Real 3-D objects have more depth information than outline drawings, but also extra information about identity (eg texture, hardness, temperature). Previous studies have not manipulated the availability of depth information in haptic object recognition whilst controlling for other information sources, so the importance of depth cues has not been assessed. In the present experiments, people named plastic small-scale models of familiar objects. Five versions of bilaterally symmetrical objects were produced. Versions varied only in the amount of depth information: minimal for cookie-cutter and filled-in outlines, partial for squashed and half objects, and full for 3-D models. Recognition was faster and much more accurate when more depth information was available, whether exploration was with both hands or just one finger. Novices found it almost impossible to recognise objects explored with two hand-held probes whereas experts succeeded using probes regardless of the amount of depth information. Surprisingly, plane misorientation did not impair recognition. Unlike with vision, depth information, but not object orientation, is extremely important for haptic object recognition.

1 Introduction

Raised-line drawings of familiar nameable objects are usually extremely difficult to identify haptically, although even congenitally blind people can succeed at this task (eg Heller 1989; Heller et al 1996; Kennedy and Bai 2002; Klatzky et al 1993; Lederman et al 1990; Loomis et al 1991; Magee and Kennedy 1980; Scocchia et al 2009; Symmons and Richardson 2000; Thompson et al 2003, 2006; Wijntjes et al 2008a, 2008b). Much of the research on haptic recognition of raised-line drawings has compared the performance of blind to sighted participants to investigate the role of visual experience and visual imagery on this task (see, for example, Lederman et al 1990; Thompson and Chronicle 2006), though this topic will not be considered here. Error rates for recognising raised-line drawings vary widely across studies but are usually more than 50% and can be over 90%. In addition, recognition is usually extremely slow: over 1 min of haptic exploration is often required.

In contrast to this poor performance with raised-line drawings, real 3-D objects are identified much more quickly and accurately. For example, Klatzky et al (1985) tested people's ability to identify a set of 100 everyday objects haptically, which could be picked up and manipulated. There were under 5% errors and responses were typically made in under 2 s. Studies in which people have not been allowed to pick up or to move objects have shown slower performance, suggesting that information about an object's weight and moving parts is important for recognition. Nevertheless, recognition performance remains far superior to that typically reported for raised-line drawings. For example, Craddock and Lawson (2008, 2009a) and Lawson and Edwards (2011) reported 4% – 12% errors and responses of 3 – 5 s for naming real everyday objects fixed to tiles. Similarly, in their baseline study, Klatzky et al (1993) reported 5% errors and mean reaction times (RTs) of 6 s.

Klatzky et al (1985) suggested that an important difference between raised-line drawings and real 3-D objects is that identifying drawings requires shape to be extracted, whereas for 3-D objects other cues, such as texture, are available. However, the results of previous studies do not permit strong conclusions to be drawn about the importance of non-shape information in producing the recognition advantage for real 3-D objects over raised-line drawings since their identification was not directly contrasted across comparable sets of stimuli. Heller et al (2006) suggested that "haptic pictures can yield high levels of performance, and need not suffer when compared with 3-D objects" (page 1417) and noted that performance in their experiments—testing the matching of raised-line drawings to 3-D geometric shapes (pyramid, cube, etc)—was often superior to the haptic recognition of human faces. However, comparing results across such poorly-matched stimuli does not provide strong support for their claim.

In the present study, we investigated how the availability of depth information and restrictions on exploratory strategies influenced people's ability to haptically recognise stimuli which were matched except for the presence of depth cues to shape. The real 3-D objects tested by Craddock and Lawson (2008, 2009a), Klatzky et al (1985, 1993), and Lawson and Edwards (2011) had more depth information than raised-line drawings, but also many other potential sources of information about object identity, such as size and hardness. The results of Lawson (2011) suggest that these latter cues may play an important role in recognition. Lawson (2011) tested the speeded naming of visually and haptically presented plastic small-scale models of familiar objects. Haptic naming was poor (9 s RT, 44% errors) and visual naming of the same stimuli was also quite difficult (1.3 s RT, 15% errors). This relatively poor performance may have been in part due to the use of stringent criteria for correct responses and the inclusion of similarly shaped items. However, it was probably also due to the lack of non-shape cues (such as size and texture) for these scale models. People's ability to haptically identify 3-D models of objects in Lawson (2011) fell between the efficient recognition of freely explored real everyday objects (Klatzky et al 1985) and the very poor recognition of drawings whose very nature (raised lines on a flat surface) greatly restricts what information is available and which exploratory strategies are useful.

Shape information usually dominates over other cues for visual object recognition but this may not be the case for haptics. Cooke et al (2007; see also Cooke et al 2010) reported that multidimensional scaling analyses using similarity ratings from 3-D novel objects indicated that texture and shape information were similarly important for haptics, whereas shape cues were much more important than texture cues for vision (see also Lakatos and Marks 1999). This is consistent with Klatzky et al's (1985) suggestion that extra non-shape cues might explain much of the recognition benefit for 3-D over raised-line drawings. In addition, many of the raised-line drawings used previously were nonrealistic representations of objects and included pictorial conventions, such as perspective information, which may not have been interpreted appropriately.

Klatzky et al (1993) came closest to directly comparing the effects of depth cues on haptic object recognition. Their participants wore a thick glove to haptically explore real 3-D objects. The glove attenuated non-shape information such as temperature, hardness, and texture. Performance was compared to bare-handed exploration of raised-line drawings produced from two-thirds-real-size fixed-view photographs of the same 3-D objects, so relative size information was preserved. Raised-line drawings of objects remained much harder to recognise, at around 80 s RT and 75% errors, for both whole-hand and single-finger exploration, with rather worse performance in the latter case. In contrast, recognition of the 3-D objects was quite good despite the glove. Indeed, free exploration with a glove (16 s RT, 7% errors) was about as accurate as bare-handed exploration (6 s RT, 5% errors) although much slower. Single finger exploration with a glove (45 s RT, 26% errors) was substantially worse, but remained much better than the recognition of raised-line drawings.

However, Klatzky et al's (1993) glove manipulation did not permit a pure test of the contribution of depth information to haptic object recognition. First, it did not eliminate all non-shape cues, such as hardness. Second, the glove removed some fine, structural information, so it influenced the availability of shape as well as non-shape cues. In a second experiment, the gloved conditions were repeated but with cutaway fingertips, making available information about the object's material and fine spatial detail. Here, overall performance was similar to when the full glove was worn, suggesting that the information removed by preventing direct skin contact was helpful to recognition but was not the primary source of identity cues.

Instead of using Klatzky et al's technique of indirectly varying which cues to identity were available, in the present experiments non-shape information was removed from the stimulus itself. The availability of depth cues was then manipulated across matched versions of the same object. This permitted a direct test of the ability of the bare hand to identify different versions of the same objects using shape information alone. In order to vary depth cues whilst keeping all other aspects of the stimulus (object material, texture, size, and so on) constant, the 3-D stimuli were represented by non-realistic small-scale plastic models rather than by real everyday objects. Useful depth information was then progressively removed from these 3-D models until only its outline contour provided identity-specific information for the cookie-cutter stimuli (see figure 1).

Finally, it is worth considering whether such outline contours are meaningful stimuli for haptics. Visual object recognition of line drawings is extremely good and is broadly comparable to that of other types of stimuli such as photographs and shaded drawings

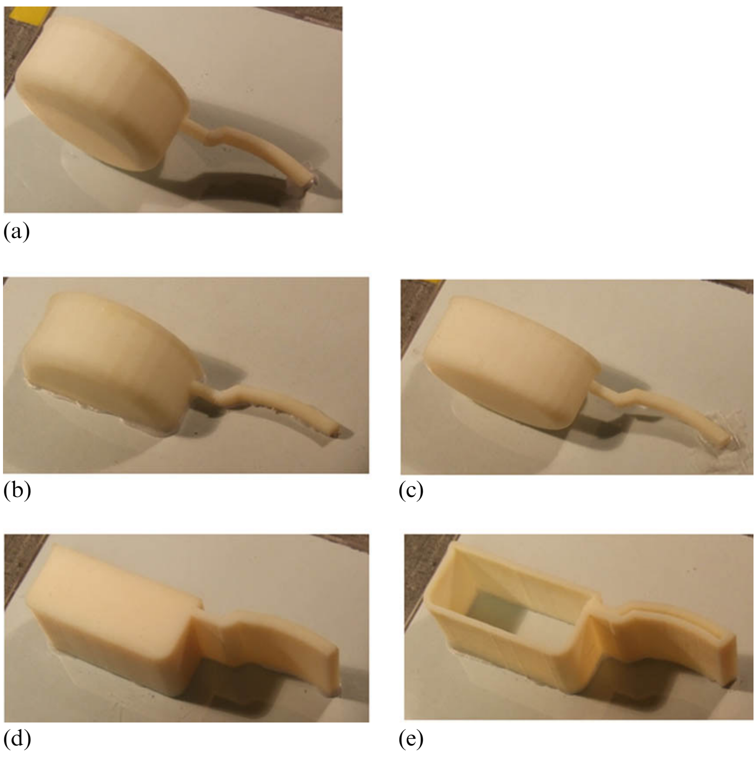


Figure 1. [In colour online, see http://dx.doi.org/10.1068/p6786] The five versions of the saucepan, with full, partial, and no depth information in the top, middle, and bottom row, respectively: (a) 3-D, (b) half, (c) squashed, (d) plane, (e) cookie-cutter.

(Brodie et al 1991; Cole et al 2009; Wagemans et al 2008). This is likely, because line drawings preserve most of the important shape information about an object, since this can usually be derived from the occluding contour of an object. In normal circumstances, the loss of information from shading, colour, texture, and so on has only modest effects on visual object recognition since the occluding contour provides rich and salient shape information. However, shape seems to be more important for vision than for haptics (Cooke et al 2007, 2010). Furthermore, defining the occluding contour of an object requires specifying a fixed viewpoint, since the occluding contour is the edge on the object's surface that is tangential to the line of sight from that viewpoint. Object surfaces beyond this edge are hidden from view by other parts of the object. Monocular vision provides a single, fixed viewpoint while binocular vision provides little extra information about the self-occluded back half of an object. Head movements are necessary to see occluded sides of the object but are not usually required to recognise objects visually. In contrast, objects presented haptically do not self-occlude in the same well-specified manner, since the hand can usually touch all or most sides of an object. The haptic equivalent of the occluding contour for vision occurs only in unusual situations, such as if an object is part-buried in concrete. Thus, haptics might have difficulty in interpreting stimuli like line drawings, because these stimuli do not map readily onto the information available from feeling a 3-D object.

This observation can be countered in two ways. First, there is excellent crossmodal transfer of object information between vision and haptics (Easton et al 1997a, 1997b; Lawson 2009; Newell et al 2001; Norman et al 2004; Reales and Ballesteros 1999). Thus, even if the input from haptically explored outline contours is not directly interpretable by haptics, it could be identified efficiently by matching it to stored visual representations. Second, the claim that haptics do not perceive occluding contours is not universally acknowledged. For example, Kennedy and Juricevic (2006, page 82) argued that "curved surfaces [such as the sides of a wine bottle] have occluding boundaries between front and back for haptics, much as they do in vision". In addition, the results of studies by Heller and colleagues (Heller et al 2002, 2006, 2009) suggest that the occluding contour has some meaning haptically since even early-blind participants who have had no visual experience can interpret raised-line drawings. Notwithstanding these results we would argue that, unlike with vision, most parts of an object can be explored haptically (at least for those like the relatively small moveable objects tested here) and there is typically no well-specified occluding contour.

In experiment 1, we compared people's recognition of five versions of the same set of everyday objects which systematically varied the amount of depth information available. Versions with no useful or with full depth information were then presented again in two further studies. In experiment 2, people's exploration strategies were manipulated. One group was restricted to using a single finger to feel the stimuli and another group could only feel the stimuli indirectly, using probes (two pens). Their performance was compared to that of the people tested in experiment 1 who freely explored the stimuli with both hands. Finally, in experiment 3, we tested whether plane misorientation effects occur for haptics as they do for subjects using vision.

2 Experiment 1

Different versions of 18 familiar, nameable objects (eg cup, pear) were presented haptically to five groups in experiment 1 (see figures 1, 2, and 3). The depth cues available ranged from full information for the 3-D model of the object, through partial information for the squashed and half object versions, to no depth information for the raised surface (plane) and the raised-outline (cookie-cutter) versions of the object.

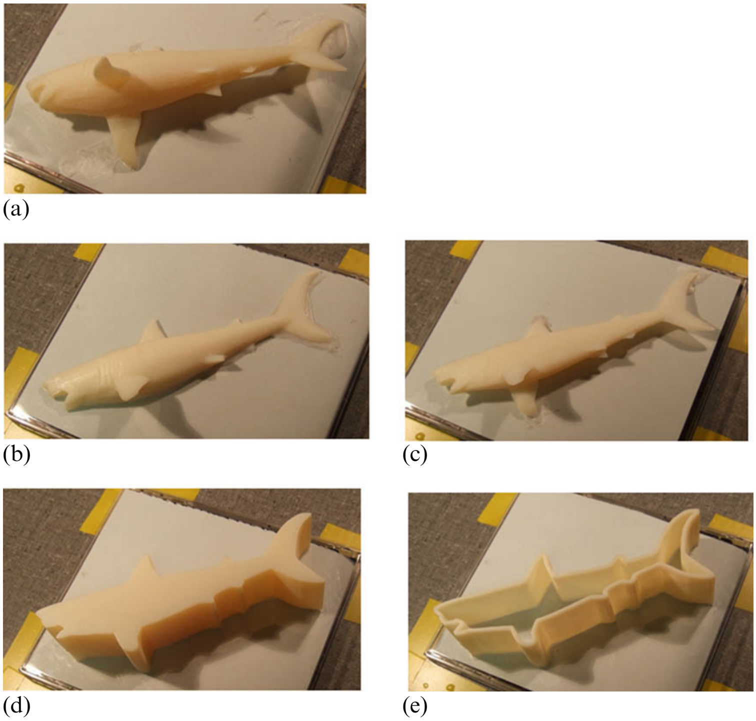


Figure 2. [In colour online.] The five versions of the shark with full, partial, and no depth information in the top, middle, and bottom row, respectively: (a) 3-D, (b) half, (c) squashed, (d) plane, (e) cookie-cutter.

Squashed stimuli were distorted versions of the 3-D objects in which the axis perpendicular to the axis of bilateral symmetry was reduced by 50%. This altered the stimulus shape (so the cup cross-section was elliptical rather than circular) but retained all parts in the same relative positions. Half stimuli comprised one half of the 3-D object, which was split along the axis of bilateral symmetry. There was thus no shape information from one side but full, accurate information from the other side.

The cookie-cutter and plane versions comprised only the outline contour of a side-on view of the 3-D object taken perpendicularly to the axis of bilateral symmetry. Thompson et al (2003) reported that plane versions (32% errors) were identified more accurately than raised-line versions (43% errors) of the same set of objects. This advantage could be because only plane versions explicitly and locally specify the inside versus the outside at any point along an edge. Alternatively, it might be because edge detection is easier for plane stimuli. Most previous studies presenting raised-line drawings used special, swell paper which produces lines raised up to only around 1 mm above the background paper, and often much less than this (for example just 0.2 mm for Scocchia et al 2009). One important reason for the poorer performance of haptic than visual object recognition is the relatively slow, sequential acquisition of information by haptics (see Craddock et al, submitted; Loomis et al 1991; Martinovic et al, submitted). The disadvantage for serial processing may be exacerbated if raised-lines are used which are difficult to track by touch. Magee and Kennedy (1980) found superior recognition of raised-line drawings when the participant's finger was guided by an experimenter, suggesting that planning motor actions interferes with identification. Performance in this experimenter-guided condition was similar even when there was no raised-line to follow, suggesting that cutaneous information did not substantially supplement kinaesthetic information from tracking the position of the limb and finger in space. In contrast to swell paper raised-line drawings,

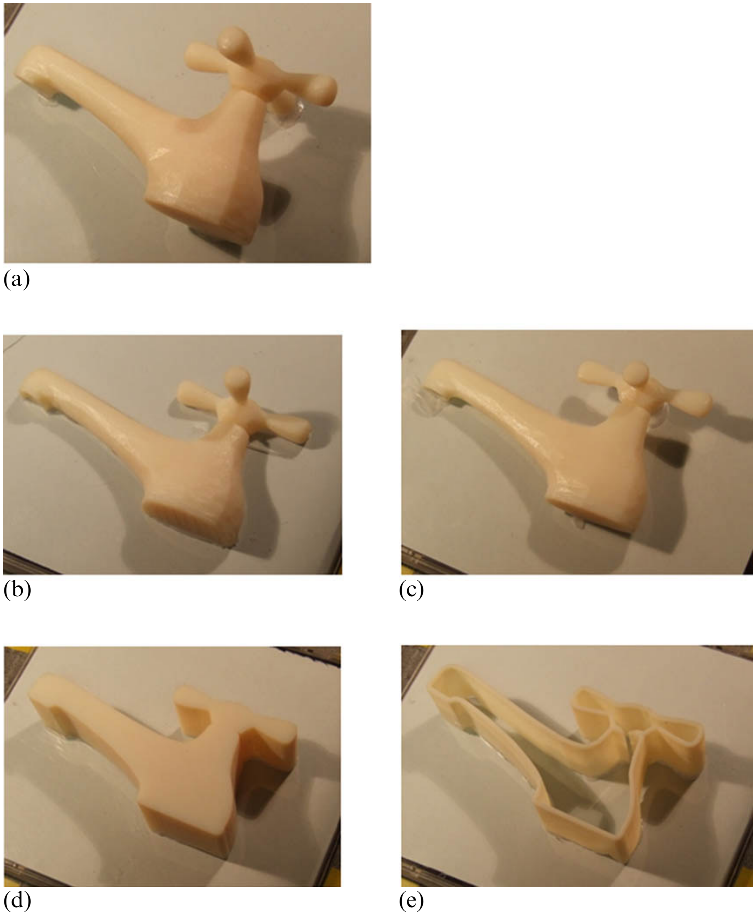


Figure 3. [In colour online.] The five versions of the tap with full, partial, and no depth information in the top, middle, and bottom row, respectively: (a) 3-D, (b) half, (c) squashed, (d) plane, (e) cookie-cutter.

the cookie-cutter stimuli used here were raised several millimetres above the base providing a distinctive, well-defined edge. If difficulty in tracking the lines was an important reason why previous studies found very poor recognition of raised-line drawings, then performance should be better with the present cookie-cutter stimuli. Any such effect could, in turn, have important implications for the design of outline pictures and diagrams for the blind.

2.1 *Method*

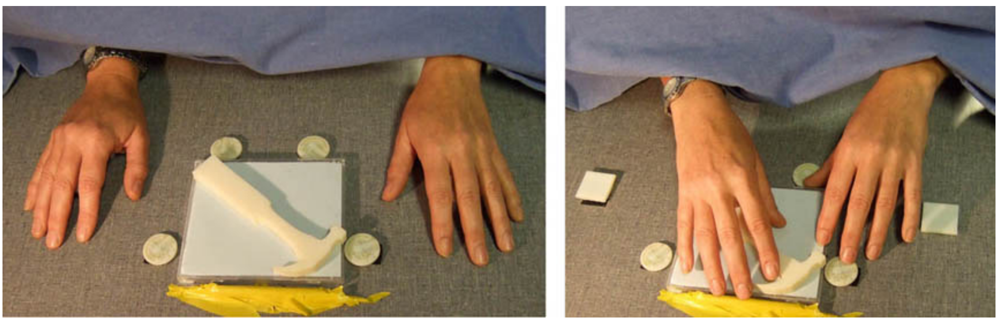
2.1.1 *Participants.* Sixty volunteers took part in the study (eleven male, seven left-handed, mean age 19 years). No participant in the experiments reported in this paper took part in more than one study.

2.1.2 *Materials and apparatus.* Five small-scale representations of each of 18 familiar, 3-D objects were printed in plastic using a 3-D printer. Each of these 90 stimuli was 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. All five versions of each object were attached to the base at the same orientation and location. Each set comprised: a full 3-D model; a squashed version of the 3-D model which was distorted (squashed) by reducing the axis which ran perpendicular to the base by 50% relative to the two orthogonal axes;

the upper half of the 3-D model, divided along the axis of symmetry; the filled-in outline contour of the 3-D model (plane) for a view perpendicular to the axis of symmetry; and the plane version without internal fill (cookie-cutter) (see figures 1, 2, and 3). The outline contour is equivalent to the occluding contour given an infinite viewing distance. The lines in the cookie-cutter version were 1 – 2 mm thick. In contrast to many previous studies which used raised-line drawings, no internal edges were represented in the cookie-cutter versions and no pictorial conventions were included to suggest perspective. For example, only two of the chair legs were depicted, rather than all four being shown with the furthest two being shorter and to the side of the nearer legs. This was done to control the shape information available across the five versions.

The maximum depth of the object along the axis perpendicular to the base was identical for the half, squashed, plane, and cookie-cutter versions, and it was twice as deep for the 3-D stimuli. The two other orthogonal dimensions of the object (its height and width for the two axes parallel to the base) were identical for all 5 versions. The depth, height, and width varied across the 18 objects.(1) The average depth was 4 cm for the 3-D versions and 2 cm for the other versions, and the average height and width was 8 cm (maximum 20 cm). The stimuli were placed in a fixed location on a table. This location was marked with fixed plastic blocks (see figure 4). To the left and right of this location were small plastic squares on which participants rested their hands in-between each trial. A curtain blocked the participant's view of the stimuli.

2.1.3 *Design and procedure.* On each trial, the experimenter placed the stimulus in front of the participant, in-between his/her hands. Stimuli were oriented to be upright relative to the participant (ie with the bottom of the object nearest to the participant and the top furthest—see figure 4) with the base flat on the table. The experimenter then pressed



(a) (b)

Figure 4. [In colour online.] A participant with hands emerging from under the curtain in experiment 1: (a) hands in the resting position, touching the plastic squares at the side; (b) with both hands used to freely explore the plane version of the hammer.

(1) Printing and mounting issues meant that a few of the stimuli were not as described. The 3-D (and, to a lesser extent, the squashed) versions of some of the objects, especially the bell and iron, had to be mounted at a slight tilt, since the bottom of the object was wider than the top. This meant that the axis of symmetry was not parallel to the base, unlike in the half, plane, and cookie-cutter versions. For the bell, the cookie-cutter version was larger than the other versions in experiments 1 and 2 only, and the cookie-cutter and plane versions were not as deep as the half and squashed versions. The half, plane, and cookie-cutter versions of the dolphin were mounted on a printed plastic background rather than on a CD case. In experiment 1, the half version of the hand had the little finger misprinted, whilst in experiments 1 and 2 the 3-D version of the hand had the index finger misprinted. In experiment 1 the half version of the toilet faced left, whereas it faced right in the other four versions. Similarly, the half and 3-D versions of the head faced right, whereas it faced left in the cookie-cutter, plane, and squashed versions. There was a small dent in the 3-D version of the head. The stem of the squashed version of the pear had a different size and position relative to the other four versions.

a key on the computer keyboard to trigger an auditory signal "Go" which told the participants that they could move their hands from their resting position to touch the stimulus. People could use both hands but they were not allowed to rotate, move, or pick up the stimulus. They had unlimited time to name the 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 had named 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 RT to name the object. The experimenter then typed in the participant's response while the participant returned his/her hands to the resting position.

Everybody completed one block of 18 trials. Separate groups of twelve people felt the 3-D, squashed, half, plane, and cookie-cutter stimuli. Half of each group felt the objects in one fixed order and the other half felt them in the reverse order. One of the two block orders was dolphin, chair, hand, hammer, bottle, gun, head, saucepan, banana, scissors, bell, tap, shark, toilet, pear, lamp, cup, iron. The experiment took around 15 min to complete and there were no practice trials. Afterwards, people were asked whether they had seen any of the stimuli and what their strategy had been to try to recognise the objects.

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. For the 3-D and squashed stimuli, they were shown a picture of a toy 3-D duck. For the half stimuli they were shown a picture of a bas-relief sculpture. For the cookie-cutter and plane stimuli they were shown a picture of a set of animal cookie-cutters and animal-shaped cookies and they were told that they would feel something like the cutters or the cookies, respectively.

2.2 *Results*

In this experiment and in experiments 2 and 3 no participant was replaced, nobody reported having seen any of the stimuli during the experiment, and many participants said that they tried to use visual imagery to recognise the stimuli. ANOVAs were conducted on the inverse of the mean correct RT to reduce the influence of long RT outliers (Ratcliff 1993) and on the percentage of errors (see figure 5). There was one empty cell in the by-participants RT analyses and 13 empty cells in the by-items RT analyses. These cells were replaced by the mean for the appropriate condition. In the analyses there was one between-subjects but within-items factor of depth (the object version: 3-D, squashed, half, plane, or cookie-cutter). Here, and in experiments 2 and 3, the results for the F-value in the by-participants and by-items analyses are reported using superscripts: F^{p} and F^{i}, respectively. Unless otherwise stated, all pairwise differences noted below were significant ($p < 0.05$) in by-participants and by-items a-posteriori Newman–Keuls analyses.

Depth was significant for RT ($F^{\mathrm{p}}_{4,60} = 3.76$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.22$; $F^{\mathrm{i}}_{4,68} = 13.46$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.44$) and errors ($F^{\mathrm{p}}_{4,60} = 14.63$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.52$; $F^{\mathrm{i}}_{4,68} = 16.95$, $p < 0.001$, $\eta_{\mathrm{p}}^2 = 0.507$). For RT, plane (9.8 s), cookie-cutter (10.0 s), and squashed (9.9 s) versions were all named slower than half (8.0 s; in the by-items but not the by-participants a-posteriori analyses) and 3-D (7.1 s) versions. Accuracy was worst for plane (68% errors) and cookie-cutter (65% errors) versions, which were named less accurately than the other three versions. In addition, squashed versions (49% errors) were named less accurately than 3-D versions (25% errors), with half versions (36% errors) of intermediate accuracy. There were no significant differences in accuracy between 3-D and half, between half and squashed, and between plane and cookie-cutter versions.

2.3 *Discussion*

Recognition was hardest for the plane and cookie-cutter versions, intermediate for the squashed versions, and easiest for the half and 3-D versions. These results reflect the amount of useful depth information available for each type of stimulus: recognition was much better if more depth information was available. It was not necessary for stimuli to have full, veridical depth information: half and squashed versions of objects were identified quite accurately. Importantly, the poor recognition of the plane and cookie-cutter versions was not because people just did not try to identify them, since people spent more time exploring these stimuli. Instead, these results show that integrating sequentially acquired haptic information from the outline contour of an object is extremely difficult.

These results reveal that depth information is a critical factor in determining the efficiency of haptic object identification. It is, though, also important to note that in experiment 1 even the 3-D models with full depth information were difficult to recognise. The present results cannot be directly compared with those of other studies since different stimuli and tasks were used. However, error rates for the 3-D versions here (25%) were at least twice as high as in previous studies presenting real everyday objects for free exploration with both hands (4%–12% for Craddock and Lawson 2008, 2009a; Klatzky et al 1985, 1993). Furthermore, error rates for the present 3-D versions were more similar to those found in studies presenting a different set of small-scale plastic models of objects (Lawson 2009, 2011). These two comparisons suggest that perceptual information other than depth, such as size, texture, and hardness, provides crucial extra cues for haptic object recognition.

Unlike accuracy, the speed of identifying the 3-D stimuli (7 s) was broadly similar to that reported for other 3-D objects which could not be moved or lifted (2–6 s for Craddock and Lawson 2008, 2009a; Klatzky et al 1993; Lawson 2009, 2011). In contrast, the cookie-cutter versions were identified several times faster (12 s) than has typically been reported for the recognition of raised-line drawings. There was also no difference between the plane and cookie-cutter versions, contrary to the findings of Thompson et al (2003). Details were not provided in their paper, but the description of their stimuli suggests that the lines defining their raised-line stimuli were harder to detect than the edges of their plane stimuli. Their raised-line drawings were produced with swell paper so were probably under 1 mm high and similarly narrow and difficult to trace; mean RTs were 35 s. In contrast, little motor control was needed to run a finger along the top of the well-defined edges of our cookie-cutter stimuli and responses were three times faster. Note that no useful information about identity was available from the height of our cookie-cutter stimuli. This height was constant for a given stimulus; only the 2-D location of the outline was informative. Specifying contours with plastic lines rather than swell paper may allow people to extract information much faster and this, in turn, may aid haptic recognition. If so, then this could provide a simple means to improve pictures and diagrams made for partially sighted and blind people. We intend testing this hypothesis directly by comparing the recognition of the same outline stimuli produced with swell paper versus plastic printing.

3 Experiment 2

In experiment 2 the way people could acquire information from the 3-D and plane versions was restricted to determine whether the advantage for full-depth stimuli found in experiment 1 remained when both versions had to be explored with similar movements. The 3-D and plane versions were tested because they spanned the range from full to no depth information and they were, respectively, the easiest and hardest stimuli to identify in experiment 1. Relative to the two-handed exploration permitted in experiment 1, haptic exploration was restricted in two ways. One group could only use one finger to explore, whilst a second group had to use probes (two pens) to feel the objects indirectly. The motivation for testing these two manipulations are considered in turn below.

Lederman and Klatzky (1987; see also Klatzky et al 1987; Lederman and Klatzky 1990, 2004) classified the main types of hand movements used for exploring real everyday 3-D objects. Important exploratory procedures included lateral movement to test texture or roughness, pressure to assess hardness, unsupported holding to indicate weight, enclosure for global shape and contour-following for local shape. Only enclosure and contour-following code for shape properties. The other exploratory procedures would be uninformative for the plastic models tested here (see also Cooke et al 2010). Relative to the more specialised procedure of contour-following, enclosure is usually faster and is employed earlier in exploration. Typically, enclosure provides more gross large-scale shape information than contour-following (Lederman and Klatzky 1990), though for speeded responses enclosure can be informative about salient local features (Plaisier et al 2009).

In experiment 1, people freely explored the stimuli using both hands. This may have benefitted the 3-D, squashed, and half versions because enclosure with the whole hand could quickly extract overall, global shape. In contrast, observation of people feeling the cookie-cutter and plane stimuli revealed that they often only used contour-following, sequentially feeling with one finger along the outline edge of the stimulus.

It is not yet known what determines when people spontaneously use a single finger versus one hand or both hands to explore haptic stimuli. Many aspects of the stimulus (such as size, symmetry, and depth cues) and other factors (such as individual differences and whether the participant is seated or standing) may play a role. Symmons and Richardson (2000) found that single-finger exploration was used about two-thirds of the time when people had to haptically recognise raised-line drawings similar in size to our stimuli. The next most common strategy was holding multiple fingers close together to form a single, larger surface. People rarely used multiple fingers of one hand to simultaneously explore different parts of the stimulus. In contrast, Wijntjes et al (2008a) reported that both hands were used about two-thirds of the time during free exploration of raised-line drawings. They used both small (10 cm, similar to our stimuli) and large (35 cm) stimuli. However, here the preference for two-handed exploration of small stimuli may have been because the two sizes of stimuli were presented in an alternating sequence.

In experiment 2, rather than just observing people's preferred exploration strategies, we restricted which strategies could be used. Requiring single-finger exploration prevented objects from being enclosed. Since there were no non-shape cues to identity, this forced people to rely on contour-following. This was only expected to disadvantage the recognition of 3-D versions, since enclosure was not predicted to be useful for identifying plane versions. Requiring the use of probes (pens) to feel the stimuli assessed the importance of accurately accumulating depth information available from direct skin contact. Unlike probes, the finger pad provides information about fine-scale shape over a small area. Pilot testing revealed that it was extremely hard to recognise stimuli with a single probe, so people were given two probes to try to make the task easier. With two probes, one could be kept as a static marker, so that exploration was relative to a fixed point, which could help to define a spatial reference frame during exploration.

Similar manipulations to those used in experiment 2 have been tested in previous studies of haptic object recognition. Klatzky et al (1993) and Lederman and Klatzky (2004) investigated how restricting haptic exploration influenced the recognition of everyday real objects and a matched set of raised-line drawings. Exploration of real, 3-D objects with both hands (6 s RT, 5% errors) was much faster than single-finger exploration (31 s RT, 8% errors) which, in turn, was far superior to the use of a single probe (85 s RT, 40% errors). The single probe was a 15 cm shaft with a 2–4 mm elliptical tip, so was similar to the pen probes used in experiment 2. Raised-line drawings were much harder to recognise than 3-D objects whether exploration was with the whole hand (around 75 s RT, 70% errors) or a single-finger (90 s RT, 83% errors). Similarly, Wijntjes et al (2008b) found 10% more errors for one-handed than for two-handed exploration of raised-line drawings. In contrast, Loomis et al (1991) failed to find a difference between one-finger versus two-finger exploration for the recognition of raised-line drawings. However, this null finding may have been because their manipulation did not produce a sufficiently large change in the field of 'view', particularly since people were told to hold both fingers together in the two-fingered condition.

In summary, restricting exploration from two hands to one hand or to just one finger or only allowing indirect stimulus contact via a probe usually slows exploration and/or increases errors. However, the 3-D stimuli tested by Klatzky et al were real everyday objects. In contrast, experiment 2 compared people's ability to identify 3-D and plane stimuli which lacked non-shape cues to identity (such as hardness, size, texture) and which differed only in the amount of depth information provided. Performance by the two-pens group was extremely poor so, in addition, four experts were tested in this condition to test the effect of prior knowledge of the stimuli.

3.1 *Method*

3.1.1 *Participants.* Forty-eight volunteers with no prior experience of the stimuli took part in the study (eleven male, two left-handed, mean age 21 years). Of these, twenty-four were allocated to the one-finger group and twenty-four to the two-pens group. In addition, four experts were tested in the two-pens condition, all of whom were visually familiar with the objects. These experts (one male, none left-handed, mean age 29 years) comprised the first author, the two research assistants who tested most of the participants in experiments 1 and 2, and a graduate student who was given a 20 min visual training session with the stimuli immediately before being tested. They had little or no experience of haptically recognising the stimuli.

3.1.2 *Materials and apparatus.* These were identical to those in experiment 1. In addition, two identical pens with caps were used. These were 145 mm long and the tips of their caps were approximately 2 mm in diameter.

3.1.3 *Design and procedure.* The procedure was identical to that in experiment 1 except for the mode of exploration. Participants in the one-finger group were told to feel the stimuli with the index finger of their preferred hand. They were monitored to ensure compliance with this instruction. Participants in the two-pens group were given one pen to hold in each hand. They could hold the pen at any point but they were told not to touch the pen caps and to feel the stimuli with the tips of the caps only. They were instructed not to touch the stimuli with any part of their hand and the experimenter checked that they did not do this. The experimenter told the participants in both groups where to move their fingers or pens if they failed to locate the stimulus at the start of the trial or if they moved away from the stimulus during a trial. In both groups, twelve people felt the 3-D versions and twelve felt the plane versions. The experts felt the 3-D and the plane versions in two separate blocks, with stimulus order counterbalanced across the four participants. Two new item orders were generated for the experts since three experts were familiar with the orders used in experiments 1 and 2.

3.2 *Results*

ANOVAs were conducted on the inverse of the mean correct RT and on the percentage of errors for the one-finger and two-pens group in experiment 2 and the 3-D and plane both-hands group from experiment 1. The analyses included data from seventy-two people in three haptic exploration groups (one finger, two pens, and both hands) with each group comprising twelve people who felt 3-D versions and twelve who felt plane versions.

Empty cells were filled with the mean for the appropriate condition. In the by-participants RT analyses there was 1 empty cell in the both-hands group and 6 empty cells in the two-pens group. In the by-items RT analyses there were 6 empty cells in the both-hands group, 1 empty cell in the one-finger group, and 22 empty cells in the two-pens group. In all analyses there were two factors: depth (3-D or plane) and exploration (one finger, two pens, or both hands). These factors were both between-subjects for the by-participants analyses and were both within-subjects for the by-items analyses. Unless otherwise stated, all pairwise differences noted below were significant ($p < 0.05$) in by-participants and by-items a-posteriori Newman–Keuls analyses.

Depth was significant for RT ($F^{\mathrm{p}}_{1,66} = 9.668$, $p < 0.004$, $\eta^2_{\mathrm{p}} = 0.13$; $F^{\mathrm{i}}_{1,17} = 36.64$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.68$) and errors ($F^{\mathrm{p}}_{1,66} = 68.24$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.51$; $F^{\mathrm{i}}_{1,17} = 62.59$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.79$). Plane versions (18.9 s RT, 78% errors) were harder to name than 3-D versions (14.1 s RT, 52% errors).

Exploration was significant for RT ($F^{\mathrm{p}}_{2,66} = 103.866$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.76$; $F^{\mathrm{i}}_{2,34} = 425.412$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.96$) and errors ($F^{\mathrm{p}}_{2,66} = 88.51$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.73$; $F^{\mathrm{i}}_{2,34} = 95.58$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.85$). There were substantial differences between all three conditions. Naming was faster and more accurate for the both-hands group (8.2 s RT, 47% errors) than the one-finger group (26.0 s RT, 55% errors) which, in turn, was faster and more accurate than the two-pens group (38.4 s RT, 93% errors). The near-floor performance of the two-pens group was not due to people giving up after only briefly exploring the stimulus. The mean RT for all of their trials (rather than only the correct trials as reported above) was 66.9 s and 74.6 s for plane and 3-D versions, respectively so, typically, over a minute was spent trying to recognise each object. This effort was, though, to no avail. On average, people in the two-pens group recognised just one object.

Finally, the interaction of depth × exploration was significant for RT ($F^{\mathrm{p}}_{2,66} = 3.944$, $p < 0.03$, $\eta^2_{\mathrm{p}} = 0.11$; $F^{\mathrm{i}}_{2,34} = 23.361$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.58$) and errors ($F^{\mathrm{p}}_{2,66} = 18.46$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.36$; $F^{\mathrm{i}}_{2,34} = 20.11$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.54$) (see figure 5). Plane versions were named slower and less accurately than 3-D versions for the both-hands group

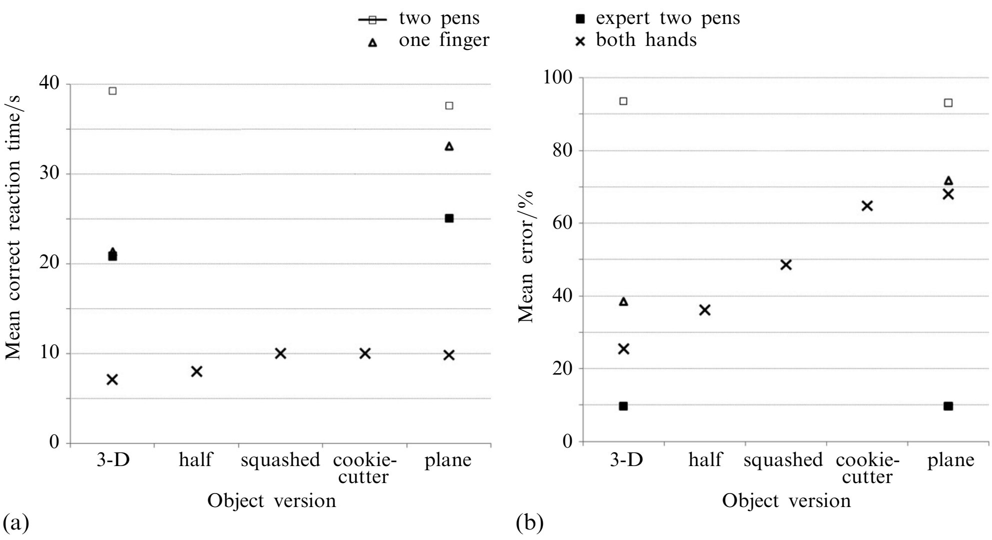


Figure 5. Mean correct RT (a) and mean percentage errors (b) for the five groups in experiment 1 who felt the 3-D, half, squashed, cookie-cutter, or plane versions of the objects with both hands, and for the four groups in experiment 2 who felt either the 3-D or plane versions with either one finger or two pens, and for the group of 4 experts in experiment 2 who felt both the 3-D and plane versions with two pens.

(9.8 s RT and 68% errors versus 7.1 s RT and 25% errors) and the one-finger group (33.1 s RT and 72% errors versus 21.3 s RT and 38% errors; though the RT difference for the by-participants a-posteriori analysis was not significant). However, performance was similarly poor for both versions for the two-pens group (37.6 s RT and 93% errors versus 39.2 s RT and 94% errors). For plane versions, using both hands was faster but no more accurate than a single finger, which, in turn, was more accurate but no faster than using two pens. For 3-D versions, using both hands was faster and more accurate than a single finger which, in turn, was faster and more accurate than using two pens (the latter difference was not significant for RT for the by-participants a-posteriori analysis).

3.2.1 *Experts using two pens.* Novices in the two-pens group identified a maximum of 4 of the 18 items, with most identifying either none or just one (38.4 s RT, 93% errors). However, they were unfamiliar with the stimuli. In stark contrast, the four experts were quite good at identifying both the 3-D (20.8 s RT, 10% errors) and plane (25.0 s RT, 10% errors) versions. Thus, useful information could be extracted using two pens given sufficient visual familiarity with the stimuli and knowledge of the object set. Interestingly, though, as for the novice two-pens group, the experts were no better at identifying the 3-D than the plane stimuli, unlike the results for the both-hands and single-finger groups. The experts did not have the problem of the floor effect for the two-pens novice group. Indeed, RT for the experts fell between that for the both-hands and single-finger groups and accuracy was superior to both groups (see figure 5). Introspective reports by the experts indicated that they often engaged in explicit hypothesis-testing (does the item have a concavity? is it elongated?) rather than trying to perceive the overall shape of the object.

3.3 *Discussion*

Altering the mode of haptic exploration had a dramatic effect on the ease of recognising stimuli. The 3-D versions were identified slower and less accurately when a single finger was used rather than both hands. Thus, preventing people from using an enclosing exploratory procedure disrupted recognition when full-depth information was available. In contrast, single-finger exploration of the plane versions was no less accurate than with the use of both hands. This suggests that the plane stimuli were recognised by contour-following, and that enclosure was not a useful exploratory procedure. However, this interpretation is complicated by the observation that people were over three times slower to recognise the plane versions with a single finger (33 s) compared to when they could use both hands (10 s). Clearly, exploration was not identical in the two cases. Using both hands probably helped to guide the finger during contour following and it may also have aided location of the most informative parts of the contour, speeding up exploration. Nevertheless, the present results suggest that information could eventually be accumulated and integrated just as successfully with the use of only one finger. Further research is needed to investigate why slowing exploration did not reduce accuracy in this case. It has usually been assumed that a major reason why haptic object recognition is worse than visual object recognition is its reliance on slow, sequential accumulation of information (Craddock et al, submitted; Loomis et al 1991). It is therefore surprising that a manipulation which slowed responses over three-fold did not increase errors.

Importantly, although the advantage in accuracy for 3-D over plane versions was significantly reduced when objects were explored with just one finger (33% benefit) rather than with both hands (43% benefit), most of this advantage remained. Thus the bulk of the benefit in providing full-depth information in the 3-D versions is not simply because 3-D stimuli enable a wider variety of exploratory strategies to be used. Instead, most of this advantage appears to come from the extra shape information per se and this could be extracted even by a single finger moving sequentially across the surface of an object.

Finally, performance was extremely slow and inaccurate when either 3-D or plane versions were explored with two pens rather than by direct skin contact. Lederman and Klatzky (2004) reported similarly poor performance whether objects were explored with a rigid plastic finger sheath or with a long probe. This suggests that using a probe is not harder simply because the hand is then further from the object's surface than when exploring with a fingertip. The rigid sheath used by Lederman and Klatzky was individually moulded to the participant's index finger and was only around 1.5 mm thick, yet it did not improve the recognition of real everyday objects over that when exploring with a 15 cm long probe like the pens used here. In contrast, haptic object recognition with gloves is quite good (Klatzky et al 1993), so being able to feel with a flexible surface may be the critical factor for successful identification. The poor performance of novices in experiment 2 was not because it was impossible to use probes to gain shape information indirectly. Experts who were visually familiar with the stimuli performed quite well in the two-pens condition despite having little experience in recognising the stimuli haptically or in using probes to identify objects by touch. The three experts with most experience with the stimuli made just 3% errors. Nevertheless the experts, like the novices, showed no advantage for the 3-D over the plane versions so the use of a probe eliminated the advantage to recognition of providing full-depth cues.

4 Experiment 3

Experiment 3 was designed to compare people's ability to recognise upright and 180° plane-misoriented versions of the 3-D and cookie-cutter stimuli. Extensive research on presenting line drawings of objects visually has established that there is a complex but systematic relationship between the plane orientation of a picture of a familiar object relative to its usual, canonical upright orientation, and both the speed (eg Jolicoeur 1985; Jolicoeur and Milliken 1989) and accuracy (eg Lawson and Jolicoeur 1999, 2003) of recognition (see Lawson 1999 for a review). In contrast, as far as we are aware, the effect of plane misorientation on haptic object recognition has not been tested directly. However, some related studies are reviewed below.

As discussed in section 1, if the haptic recognition of pictures is mediated by visual imagery because the occluding contour which defines them is only meaningful to vision, not to haptics, then the cookie-cutter versions might be especially susceptible to the effects of plane misorientation. This is because there is good evidence that stored visual representations of familiar objects are coded with respect to the usual, upright orientation of the object. In addition, plane rotation disrupts the haptic recognition of both letters and Braille (Heller 1987, 1992). Plane-misoriented 3-D stimuli might also be expected to be harder to recognise, given that haptic object recognition is influenced by orientation in depth in both short-term matching (Lawson 2009) and longer-term memory tasks (eg Craddock and Lawson 2008, 2010; Ernst et al 2007; Newell et al 2001). In addition, Woods et al (2008) found that there were preferred, canonical views of both familiar and novel 3-D objects.

In addition, two recent studies showed that the visual reference frame and the ability to use vision to augment haptically acquired representations can both influence the haptic recognition of raised-line drawings. First, Scocchia et al (2009) reported that raised-line drawings were easier to recognise haptically when blindfolded people had their head and eyes directed towards the stimulus (57% errors) than when their heads were turned 90° away from it (68% errors). Second, Wijntjes et al (2008b) found that people who had failed to identify a raised-line drawing were often able to recognise it later, after viewing a sketch they made of what they had felt. This benefit only occurred if they were able to see their sketch, not if they just made the sketch or if they could only feel their sketch. Thus, visually externalising people's haptically acquired mental images aided recognition, similar to the advantage for drawing images that occurs for verbally defined stimuli (Finke et al 1989). Also, an interesting series of studies has found that several different reference frames (centred on the hand, the body, or the environment) can all influence haptic object perception (eg Kappers 2004, 2007; Volcic et al 2007, 2009). However, note that in the present study all of these spatial reference frames were both fixed and approximately aligned with each other, with the object being 180° plane-rotated within these frames.

Of most direct relevance to experiment 3, Heller and colleagues (2002, 2006, 2009) found that people are fairly good at haptically matching 3-D objects to raised-line drawings representing an object from different viewpoints (top, side, perspective). In particular, Heller et al (2006) tested simultaneous haptic matching of novel 3-D objects to plane-rotated, raised-line drawings of these objects. Performance for objects with the same orientation as the drawings (experiment 2) was similar to that when the objects were plane-rotated by 45° (experiment 3). However, participants in experiment 2 were subsequently tested in experiment 3, so similar performance across both studies might be either because there was no cost for plane rotation or because beneficial practice effects counteracted a cost for plane rotation. Heller et al also tested 12 naive people in experiment 3. Participants in this group were not compared statistically to those in the equivalent group tested in experiment 2, but were somewhat less accurate which, in turn, suggests that there might have been a cost for plane rotation. Any cost could, though, have resulted from the plane-rotated 3-D objects being presented at 45°, rather than being due to plane-rotation per se. It may be easier to represent and explore stimuli where the main axis of elongation and symmetry run along the plane of the body midline. In summary, Heller et al's (2006) results show that people can match plane-rotated stimuli but these studies were not designed to assess whether plane-rotated stimuli are harder to recognise haptically than upright stimuli. This was the aim of experiment 3.

4.1 *Method*

4.1.1 *Participants.* Thirty-two volunteers took part in the study (ten male, two left-handed, mean age 21 years) with sixteen feeling 3-D versions and sixteen feeling cookie-cutter versions.

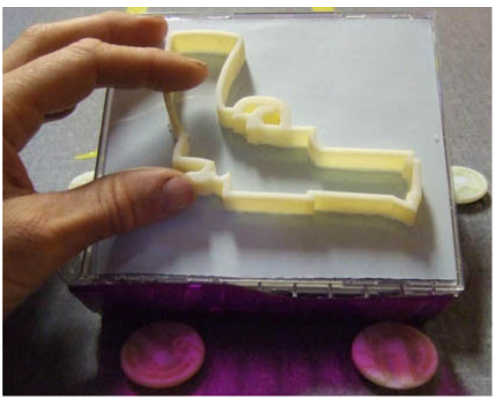
4.1.2 *Materials and apparatus.* These were identical to those in experiment 1 except for the following points. The materials were the 3-D and cookie-cutter versions of the stimuli used in experiment 1, except that the scissors and hammer were removed from the experimental set because they do not have a canonical upright orientation, the dolphin was removed because it was on a different-sized base (see footnote 1), and 5 new objects were added to increase the set size from 18 to 20. The new objects were a traffic cone, glass, camel, light bulb, and shoe, and the stimulus presentation order is given in figure 6. The shark, which was mounted diagonally in experiments 1 and 2, was re-mounted so that its main axis was horizontal and parallel to the bottom of the base (see figure 6). An angled stand (a CD holder) replaced the location where stimuli were presented in experiment 1 (see figure 7). Stimuli on this stand were at an angle of 31° from the horizontal, where 90° would mean that the stimuli were presented vertically. Stimuli were not positioned vertically, first, because this would make them difficult to explore since the participant's hands would have to flex back to feel them and, second, because it was not possible to firmly fix the heavier stimuli at steep angles.

4.1.3 *Design and procedure.* The procedure was identical to that in experiment 1 except that all stimuli were placed on an angled stand rather than flat on the table. Each stimulus was placed on the stand either upright (0°, with the top of the object furthest away from the participant and higher than the base of the object) or upside-down (rotated by 180° relative to the upright orientation—see figure 7). It could be argued that

(a)

(b)

Figure 6. [In colour online.] The full set of stimuli presented in experiment 3 shown in their upright, 0° orientation with the 3-D versions (a) and the cookie-cutter versions (b). The 20 object categories were chair, hand, bottle, gun, head saucepan, banana, bell, tap, shark, toilet, pear, lamp, cup, iron, traffic cone, glass, camel, light bulb, and shoe. Objects were presented in this order to half of the participants and in the reverse order to the remaining participants.



(a)

(b)

Figure 7. [In colour online.] (a) A participant touching the cookie-cutter version of the gun in the upside-down, 180° orientation as seen from the participant's perspective. A curtain prevented the participant from seeing the stimulus. (b) The same scene taken from the side to show that the stand tilted the stimulus and its base at an angle of 31° from the horizontal.

it makes no sense to refer to a plane rotation for haptics since no plane of rotation has a special significance for haptics, whereas the picture plane (perpendicular to the line of sight of the viewer) is always uniquely defined for vision. However, the hand is often partially or fully restricted to exploration within one plane which is then privileged, especially for 2-D stimuli like Braille letters and raised-line drawings. Furthermore, our manipulation altered the position of the top relative to the bottom of the stimulus within hand, body, and allocentric reference frames, all three of which have been found to be important for haptics (Volcic et al 2009). Thus, regardless of whether the term ‘plane rotation’ is appropriate to describe our manipulation, it influenced the perceived orientation of the object, the similarity of this orientation to that object’s usual orientation as experienced in the world, and the relation of this orientation to stored visual representations of the object.

The stimuli were presented twice, in two blocks. The orientation of the first stimulus in the first block (0° or 180°) was counterbalanced across participants, giving eight people in each subgroup. Object orientation (0° or 180°) alternated on each subsequent trial. The 20 objects felt in the first block were shown in the same order in the second block, but with the other orientation (180° or 0°). Within each subgroup of eight people, four felt the stimuli in one presentation order and the other four felt stimuli in the reverse order. People were told that objects would either be placed in their usual, upright orientation or that they would be rotated by 180° in the plane to be upside-down. Two practice trials (presenting the scissors and hammer) were given prior to each experimental block.

4.2 *Results*

ANOVAs were conducted on the inverse of the mean correct RT and on the percentage of errors (see figure 8). Empty cells were filled with the mean for the appropriate condition. In the by-participants RT analyses there were no empty cells for the 3-D group and 9 empty cells for the cookie-cutter group. In the by-items RT analyses there was 1 empty cell for the 3-D group and 18 empty cells for the cookie-cutter group.

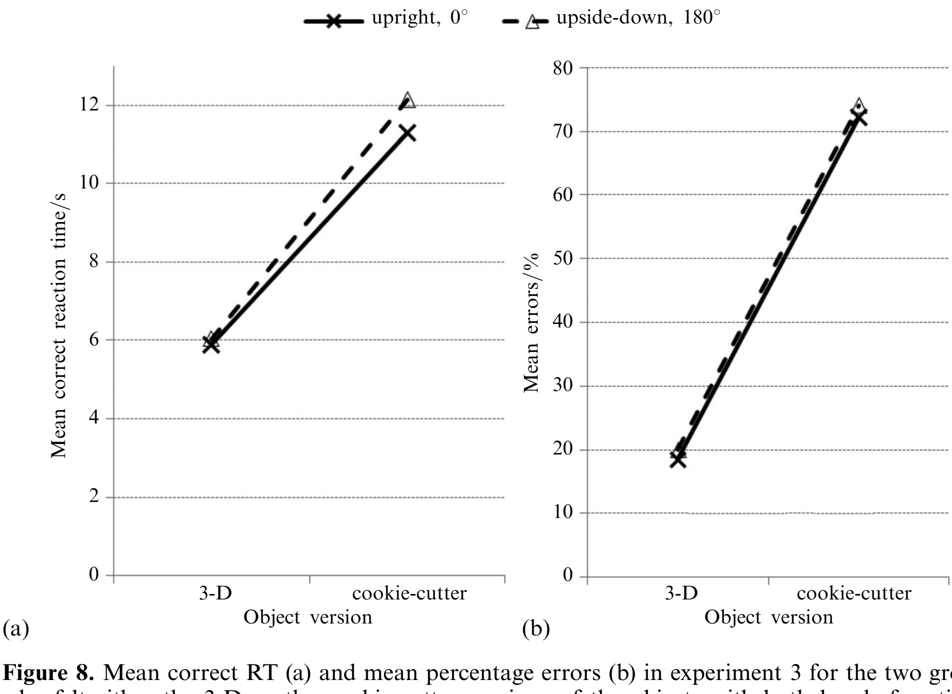


Figure 8. Mean correct RT (a) and mean percentage errors (b) in experiment 3 for the two groups who felt either the 3-D or the cookie-cutter versions of the objects with both hands for stimuli presented upright (0°) and upside-down (180°) separately.

In all analyses there were three factors: the within-subjects and within-items factors of orientation (0° or 180°) and block (1 or 2) and the between-subjects but within-items factor of depth (3-D or cookie-cutter).

Most importantly, orientation was not significant for either RT ($F^{\mathrm{p}}_{1,30} = 2.8112$, $p > 0.1$, $\eta^2_{\mathrm{p}} = 0.09$; $F^{\mathrm{i}}_{1,19} = 2.991$, $p > 0.1$, $\eta^2_{\mathrm{p}} = 0.14$) or errors ($F^{\mathrm{p}}_{1,30} = 1.121$, $p > 0.2$, $\eta^2_{\mathrm{p}} = 0.04$; $F^{\mathrm{i}}_{1,19} = 1.456$, $p > 0.2$, $\eta^2_{\mathrm{p}} = 0.07$). Upright, 0° objects (7.7 s RT, 45% errors) were no easier to name than 180° objects (8.1 s RT, 47% errors). Furthermore, no interaction involving orientation was significant. The interaction of orientation × depth is shown in figure 8.

Depth was significant for RT ($F^{\mathrm{p}}_{1,30} = 59.908$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.67$; $F^{\mathrm{i}}_{1,19} = 214.550$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.92$) and errors ($F^{\mathrm{p}}_{1,30} = 198.397$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.87$; $F^{\mathrm{i}}_{1,19} = 73.341$, $p < 0.001$, $\eta^2_{p} = 0.79$). Replicating experiment 1, the cookie-cutter versions with no depth information (11.7 s RT, 73% errors) were named slower and less accurately than the 3-D versions with full depth information (6.0 s RT, 19% errors).

Block was significant for RT ($F^{\mathrm{p}}_{1,30} = 31.575$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.51$; $F^{\mathrm{i}}_{1,19} = 34.470$, $p < 0.001$, $\eta^2_{\mathrm{p}} = 0.65$) and errors ($F^{\mathrm{p}}_{1,30} = 12.715$, $p < 0.002$, $\eta^2_{\mathrm{p}} = 0.30$; $F^{\mathrm{i}}_{1,19} = 10.788$, $p < 0.005$, $\eta^2_{\mathrm{p}} = 0.36$). Objects in block 1 (8.7 s RT, 49% errors) were named slower and less accurately than in block 2 (7.2 s RT, 43% errors).

4.3 *Discussion*

In experiment 3, people had to match haptically acquired inputs to long-term stored representations. This task was probably often mediated by visual imagery and stored visual representations of objects which code objects at their canonical upright orientation. This task would, therefore, be expected to be particularly sensitive to plane orientation compared to tasks involving either novel stimuli or simultaneous matching. However, in contrast to the well-established disruptive effects of plane misorientation on visual object recognition (Lawson 1999), people were no worse at haptically identifying upside-down compared to normally oriented, upright stimuli. This result generalised across the 3-D and cookie-cutter versions of the object (see figure 8).

This invariance to plane misorientation is surprising, given that plane-rotated letters and Braille are harder to recognise than normally oriented stimuli (Heller 1987, 1993) and that manipulating hand-, body-, and environment-centred frames of reference influences haptic performance on other tasks (Kappers 2004, 2007; Volcic et al 2007, 2009). It could be argued that the present task was so slow and difficult that any cost of mentally transforming plane-rotated representations was negligible given that such transformations can occur quickly. However, two recent studies reported that slow, inaccurate haptic recognition of raised-line drawings was influenced by related manipulations. First, Scocchia et al (2009) found that aligning eye- and head-centred reference frames with the picture orientation improved recognition performance. Second, Wijntjes et al (2008b) reported that improving visuo-spatial information by allowing people to look at sketches they had made of stimuli which they had explored haptically aided recognition of those stimuli. The present, unexpected result needs to be explored further, for example by varying the base orientation of the stimuli, by establishing whether it extends to the recognition of real everyday objects, and by testing more object categories. The present results do, though, suggest that haptic object recognition differs in an important way from visual object recognition in that it is invariant to the plane orientation of an object.

5 General discussion

The results from these three experiments showed that depth information is crucially important for the haptic recognition of familiar everyday objects, but that plane orientation is not. Experiment 1 showed that even partial or distorted depth information supported much better performance than no depth cues. Experiment 2 showed that the advantage of having depth information was not simply because it allowed more exploratory strategies to be used, although being able to enclose an object to quickly gain information about global shape played a minor role in the 3-D advantage. In contrast to the modest cost of limiting exploration to a single finger rather than both hands, restricting people to using probes to indirectly explore objects produced a dramatic drop in performance, whether or not depth information was available. Finally, experiment 3 showed that, unlike visual object recognition, plane misorientation did not disrupt haptic recognition, irrespective of whether depth information was available.

No previous study has systematically varied the amount of depth information available to aid the haptic recognition of objects. These results provide an important advance on earlier research by assessing the benefit to haptics of depth information about shape whilst controlling for the presence of other cues to identity. The current findings show that 3-D stimuli are easier to identify even after removing non-shape cues such as texture and hardness. Indeed, most of the advantage of depth information remains even if exploration is limited to using just one finger. It was only eliminated when people had to explore stimuli using probes rather than direct skin contact, indicating that contact with a flexible surface is necessary for efficient haptic identification (see also Lederman and Klatzky 2004; Klatzky et al 1993).

In order to match the different versions of each object, the cookie-cutter and plane versions tested here were outlines with no internal detail. An artist's drawing of many of the objects would have used extra lines, for example to indicate the ear for the head. The present study might, therefore, have underestimated people's ability to haptically recognise pictures of objects. However, the purpose of this study was to directly compare stimuli which varied in the amount and type of depth information available, not to determine whether other cues (for example, lines to indicate perspective) can be used to compensate for the lack of this information.

Finally, the contours of the cookie-cutter stimuli used here were defined clearly, using hard plastic lines which were raised well above the background surface. These stimuli are probably easier to explore than raised-line drawings made with swell paper or similar material. Since plastic outline stimuli can now be printed quite easily, this difference may be of practical importance when producing pictures or diagrams for partially-sighted or blind people. However, the recognition of matched plastic versus swell-paper raised-line stimuli needs to be compared directly before such a recommendation can be made.

In conclusion, these results indicate that spatial information plays a different role in haptic compared to visual object recognition. Haptics, unlike vision, is extremely sensitive to the availability of depth information. In contrast, vision, but not haptics, is sensitive to whether objects are presented at their usual plane orientation. These findings extend a recent body of evidence suggesting that the achievement of object constancy for vision and haptics is broadly similar in many situations, but that these superficial similarities may be misleading since there are important differences between the two modalities. For example, there are similar costs to generalising over changes in depth rotation (Craddock and Lawson 2008; Lawson 1999, 2009; Newell et al 2001), mirror-image reflection (Craddock and Lawson 2009a), and object size (Craddock and Lawson 2009b, 2009c). However, there are also significant differences (eg Lawson 2009; Martinovic et al, submitted). The present results supplement this evidence for differences between visual and haptic object processing.

Acknowledgments. This research was supported by a Fellowship from the Economic and Social Research Council (RES-000-27-0162) and by the Max-Planck Institut für biologische Kybernetik, Tübingen, Germany.

References

Brodie E E, Wallace A M, Sharrat B, 1991 "Effect of surface characteristics and style of production on naming and verification of pictorial stimuli" *American Journal of Psychology* **104** 517 – 545

Cole F, Sanik K, DeCarlo D, Finkelstein A, Funkhouser T, Rusinkiewicz S, Singh M, 2009 "How well do line drawings depict shape?" *ACM Transactions on Graphics* **28** 28

Cooke C, Jäkel F, Wallraven C, Bülthoff H H, 2007 "Multimodal similarity and categorization of novel, three-dimensional objects" *Neuropsychologia* **45** 484 – 495

Cooke C, Wallraven C, Bülthoff H H, 2010 "Multidimensional scaling analysis of haptic exploratory procedures" *ACM Transactions on Applied Perception* **7**(1), doi:10.1145/1658349.1658356

Craddock M, Lawson R, 2008 "Repetition priming and the haptic recognition of familiar and unfamiliar objects" *Perception & Psychophysics* **70** 1350 – 1365

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

Craddock M, Lawson R, 2009b "Size-sensitive perceptual representations underlie visual and haptic object recognition" *PLoS ONE* **4**(11): e8009, doi:10.1371/journal.pone.0008009

Craddock M, Lawson R, 2009c "The effects of size changes in haptic object recognition" *Attention, Perception & Psychophysics* **71** 910 – 923

Craddock M, Lawson R, 2010 "The effects of temporal delay and orientation on haptic object recognition" *Attention, Perception & Psychophysics* **72** 1975 – 1980

Craddock M, Martinovic J, Lawson R, submitted, "An advantage for active versus passive aperture-viewing in visual object recognition"

Easton R D, Greene A J, Srinivas K, 1997a "Transfer between vision and haptics: Memory for 2-D patterns and 3-D objects" *Psychonomic Bulletin Review* **4** 403 – 410

Easton R D, Srinivas K, Greene A J, 1997b "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

Finke R A, Pinker S, Farah M J, 1989 "Reinterpreting visual patterns in mental imagery" *Cognitive Science* **13** 51 – 78

Heller M A, 1987 "The effect of orientation on visual and tactual Braille recognition" *Perception* **16** 291 – 298

Heller M A, 1989 "Picture and pattern perception in the sighted and blind: The advantage of the late blind" *Perception* **18** 379 – 389

Heller M A, 1992 "The effect of orientation on tactual Braille recognition: Optimal touching positions" *Perception & Psychophysics* **51** 549 – 556

Heller M A, Brackett D D, Scroggs E, Steffen H, Heatherly K, Salik S, 2002 "Tangible pictures: Viewpoint effects and linear perspective in visually impaired people" *Perception* **31** 747 – 769

Heller M A, Calcaterra J A, Burson L L, Tyler L A, 1996 "Tactual picture identification by blind and sighted people: Effects of providing categorical information" *Perception & Psychophysics* **58** 310 – 323

Heller M A, Kennedy J M, Clark A, McCarthy M, Borgert A, Fulkerson E, Wemple L A, Kaffel N, Duncan A, Riddle T, 2006 "Viewpoint and orientation influence picture recognition in the blind" *Perception* **35** 1397 – 1420

Heller M A, Riddle T, Fulkerson E, 2009 "The influence of viewpoint and object detail in blind people when matching pictures to complex objects" *Perception* **38** 1234 – 1250

Jolicoeur P, 1985 "The time to name disoriented natural objects" *Memory & Cognition* **13** 289 – 303

Jolicoeur P, Milliken B, 1989 "Identification of disoriented objects: Effects of context of prior presentation" *Journal of Experimental Psychology: Learning, Memory, and Cognition* **15** 200 – 210

Kappers A M, 2004 "The contributions of egocentric and allocentric reference frames in haptic spatial tasks" *Acta Psychologica* **117** 333 – 340

Kappers A M, 2007 "Haptic space processing allocentric and egocentric reference frames" *Canadian Journal of Experimental Psychology* **61** 208 – 218

Kennedy J M, Bai J, 2002 "Haptic pictures: Fit judgments predict identification, recognition memory, and confidence" *Perception* **31** 1013 – 1026

Kennedy J M, Juricevic I, 2006 "Form, projection and pictures for the blind", in *Touch and Blindness* Eds M A Heller, S Ballesteros (London: Lawrence Erlbaum) pp 73 – 93

Klatzky R L, Lederman S J, Metzger V A, 1985 "Identifying objects by touch: an 'expert system'" *Perception & Psychophysics* **37** 299 – 302

Klatzky R L, Lederman S, Reed C, 1987 "There's more to touch than meets the eye: the salience of object attributes for haptics with and without vision" *Journal of Experimental Psychology: General* **116** 356 – 369
Klatzky R L, Loomis J M, Lederman S J, Wake H, Fujita N, 1993 "Haptic identification of objects and their depictions" *Perception & Psychophysics* **54** 170 – 178
Lakatos S, Marks L E, 1999 "Haptic form perception: relative salience of local and global features" *Perception & Psychophysics* **61** 895 – 908
Lawson R, 1999 "Achieving visual object constancy across 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 three-dimensional object recognition" *Journal of Experimental Psychology: Human Perception and Performance* **35** 911 – 930
Lawson R, 2011 "Comparing visual to haptic object naming", in preparation
Lawson R, Edwards L, 2011 "Looking in the direction of your hand helps to identify 2D pictures by touch but may not aid the haptic recognition of real, 3D objects" paper presented at the Experimental Psychology Society Meeting, Oxford, 13 – 15 April
Lawson R, Jolicoeur P, 1999 "The effect of prior experience on recognition thresholds for plane-disoriented pictures of familiar objects" *Memory & Cognition* **27** 751 – 758
Lawson R, Jolicoeur P, 2003 "Recognition thresholds for plane-rotated pictures of familiar objects" *Acta Psychologica* **112** 17 – 41
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, 1990 "Haptic identification of common objects: Knowledge-driven exploration" *Cognitive Psychology* **22** 421 – 459
Lederman S J, Klatzky R L, 2004 "Haptic identification of common objects: Effects of constraining the manual exploration process" *Perception & Psychophysics* **66** 618 – 628
Lederman S J, Klatzky R L, Chataway C, Summers C D, 1990 "Visual mediation and the haptic recognition of two-dimensional pictures of common objects" *Perception & Psychophysics* **47** 54 – 64
Loomis J M, Klatzky R L, Lederman S J, 1991 "Similarity of tactual and visual picture recognition with limited field of view" *Perception* **20** 167 – 177
Magee L E, Kennedy J M, 1980 "Exploring pictures tactually" *Nature* **278** 287 – 288
Martinovic J, Lawson R, Craddock M, submitted, "Time course of information processing in visual and haptic object classification"
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, Norman H F, Clayton A M, Lianekhammy J, Zielke G, 2004 "The visual and haptic perception of natural object shape" *Perception & Psychophysics* **66** 342 – 351
Plaisier M A, Tiest W M B, Kappers A M L, 2009 "Salient features in 3-D haptic shape perception" *Attention, Perception & Psychophysics* **71** 421 – 430
Ratcliff A, 1993 "Methods for dealing with reaction time outliers" *Psychological Bulletin* **114** 510 – 532
Reales J M, Ballesteros J, 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* **118** 219 – 235
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
Symmons M, Richardson B, 2000 "Raised line drawings are spontaneously explored with a single finger" *Perception* **29** 621 – 626
Thompson L J, Chronicle E P, 2006 "Beyond visual conventions: Rethinking the design of tactile diagrams" *British Journal of Visual Impairment* **24** 76 – 82
Thompson L J, Chronicle E P, Collins A F, 2003 "The role of pictorial convention in haptic picture perception" *Perception* **32** 887 – 893
Thompson L J, Chronicle E P, Collins A F, 2006 "From 3-D objects to 2-D pictures: Enhancing 2-D tactile picture design from knowledge of 3-D haptic object recognition" *European Psychologist* **11** 110 – 118
Van Boven R W, Johnson K O, 1994 "The limit of tactile spatial resolution in humans: Grating orientation discrimination at the lip, tongue, and finger" *Neurology* **44** 2361 – 2366
Volcic R, Kappers A M L, Koenderink J J, 2007 "Haptic parallelity perception on the fronto-parallel plane: The involvement of reference frames" *Perception & Psychophysics* **69** 276 – 286
Volcic R, Wijntjes M W, Kappers A M, 2009 "Haptic mental rotation revisited: multiple reference frame dependence" *Acta Psychologica* **130** 251 – 259

Wagemans J, De Winter J, Op de Beeck H, Ploegerô A, Beckers T, Vanroos T, 2008 "Identification of everyday objects on the basis of silhouette and outline versions" *Perception* **37** 207 – 244
Wijntjes M W A, Lienen T van, 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, Lienen T van, Vestijnen 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
Woods A T, Moore A, Newell F N, 2008 "Canonical views in haptic object perception" *Perception* **37** 1867 – 1878

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 40 2011

www.perceptionweb.com