The influence of viewpoint and object detail in blind people when matching pictures to complex objects

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Abstract. We examined haptic viewpoint effects in blindfolded-sighted (BS) and visually impaired subjects: early blind (EB), late blind (LB), and very low vision (VLV). Participants felt complex objects and matched tangible pictures to them. In experiment 1, the EB and BS subjects had similar overall performance. Experiment 2 showed that the presence of a detail on the target object lowered performance in the BS subjects, and that matching accuracy was lower overall for top views for the blind subjects. In experiments 3–5, EB, LB, VLV, and BS subjects made judgments about perspective pictures of a model house with more salient object details. In experiment 3, performance was higher for side views than for corner views. Elevated side views were identified more readily than elevated corner views in experiment 4. Performance for top views was higher than for elevated side views in experiment 5, given the relative simplicity of the top-view depictions and salient details. The EB and BS participants had somewhat lower matching accuracy scores than the other groups. We suggest that visual experience is helpful, but not essential for picture perception. Viewpoint effects may vary with experience and object complexity, but the relevant experience need not be specifically visual in nature.

1 Introduction

Blind people have had relatively little experience with haptic pictures, and many researchers have assumed that visual experience could contribute to superior understanding of graphic displays. While Kennedy and his colleagues (Kennedy 1993; Kennedy and Juricevic 2006) have argued that people who were born without sight can understand perspective, it has been more common to assume that the early blind could have some difficulty when attempting to relate solid objects to 2-D depictions. Thus, Holmes et al (1998) proposed that people using haptics might have substantial problems representing depth information in just two dimensions—in haptic pictures, for example.

Blind people may make the assumption that there is some intrinsic difficulty in depicting a 3-D world on a flat surface. The first author, MAH, has heard this sort of concern from many early-blind individuals. They often claimed that it was inconceivable to them how one might depict a solid object in 2-D form. However, it is not at present known if any difficulties that may arise in processing information from haptic pictures could derive from a lack of visual experience in early-blind persons, or from some other factor. Blind people may have limited familiarity with pictures, per se, and it is likely that this could render picture perception tasks more difficult. Moreover, we do not currently know if it is important to have specifically visual sensory experience (Cornoldi and Vecchi 2000; Lederman et al 1990), or if it is simply experience that matters, even if the experience had been in haptics. It is likely that haptic experience can substitute for vision in early-blind persons (see Millar 1994).

Revesz (1950) proposed that haptics is limited to the apprehension of global form, and one might expect deficiencies in haptic perception of detailed object characteristics (but see Heller and Clyburn 1993). Heller and Clyburn (1993) found a different pattern of responses between blind subjects and blindfolded-sighted subjects when presented with a tactile analog of a global versus local processing task. The early-blind subjects responded locally when exploring large Braille patterns comprised of different,

smaller Braille characters. The authors concluded that Braille is size-specific, unlike some other configurations derived from geometrical forms. Also, Lederman and her colleagues (1990) have proposed that touch may have difficulty with haptic representations of 2-D space, unless subjects are able to recode haptic information into visual representations. On this view, one might expect that early-blind persons would be deficient in their perceptual interpretations of haptic pictures. According to Revesz, haptics is limited in its ability to relate parts to wholes, or to understand perspective. Moreover, Klatzky et al (1993) have shown that blindfolded-sighted subjects may have difficulty naming pictures of unfamiliar objects, but can name the objects themselves. They proposed that haptics is best suited for picking up the substance-related characteristics of objects, namely hardness, softness, texture, and so on. The addition of texture to tangible drawings has been shown to influence picture perception in haptics (Thompson et al 2003), and the same holds true for vision (Rossion and Pourtois 2004).

Viewpoint effects may be influenced by visual experience. Early-blind individuals generally lack much exposure to tangible pictures, and are less likely to know much, if anything, about linear perspective (see Heller et al 2002). In some earlier research, persons with very low vision showed improved performance in a variety of picture perception tasks (see Heller 2006 for a detailed discussion of this issue). These individuals have the ability to see light and localize strong light sources. The presence of light perception can aid mobility and perhaps the development of good spatial skills. This is the reason for distinguishing this group of persons from other groups of blind individuals. The mere ability to discriminate light levels may allow a person to distinguish between sky and ground, and this visual information could support an upright posture. Maintenance of an upright posture may aid the development of spatial skills and mobility. Also, the ability to see a lamp or strong light source can reduce veer as an individual with very low vision attempts to walk directly towards a target.

The effect of viewpoint on the interpretation and recognition of haptic pictures and of objects has been examined by earlier researchers. Thus, Newell et al (2002) reported that the backs of objects were the preferred vantage points for touch. Viewpoint is closely linked to linear perspective, since perspective will vary with vantage point (Heller et al 2002, 2006). One might expect that early-blind persons would not understand linear perspective, since they lack experience with this feature of visual experience (see Heller 1989; Heller et al 1996). However, blind people can be sensitive to perspective information (Heller et al 2002, 2006). Heller et al (2002) proposed that the top views of very simple geometrical solids were the easiest pictures for blind and blindfolded-sighted people to understand. Moreover, the interpretation of elevated foreshortened views of a model house at an angle can be difficult for blind and blindfolded-sighted individuals (Heller et al 1995).

The issue of viewpoint dependence has been rather controversial in the visual literature. Some researchers have argued for viewpoint independence (eg Biederman 2001; Biederman and Gerhardstein 1993). Others, notably Tarr and his colleagues (Tarr et al 1995, 1997, 1998), have proposed that there may be preferred views, and that this may vary with familiarity and experience, the complexity of forms, and the presence of object details. However, it is not clear which sorts of views might be canonical for touch, since all of us have limited experience with tangible pictures, and many early-blind persons have none. Heller (1989) reported that some blind subjects failed to recognize a tangible picture of a telephone, because they said that the depiction of the corded phone lacked a cord. Apparently, the presence or absence of details may be diagnostic for picture recognition for some blind people.

The present experiments were designed to determine if viewpoint effects would be found with haptic pictures of more complex forms in blind people. Experiment 1 was based on experiment 6 in Heller et al (2006), but included samples of visually impaired

participants. In experiment 2 the effect of visual experience and the presence of object details on viewpoint effects in haptic pictures was tested. Experiments 3–5 were devoted to evaluating viewpoint effects in a different 3-D solid—a model house that was used in earlier research (see Heller et al 1995). We expected that early-blind participants would have problems with pictures of complex objects, especially those showing depth and solidity. Moreover, the addition of object detail could alter any possible effects of viewpoint (see Tarr et al 1997).

2 Experiment 1. Viewpoint effects in visually impaired people with complex objects

The first experiment was designed to determine if visual experience would influence viewpoint effects with relatively complex objects. In earlier research with blindfolded-sighted subjects by Heller et al (2006), there were no advantages for top views of these complex objects in the accuracy of matching tangible pictures to solid objects. It was not known if viewpoint effects would be found in visually impaired participants with these relatively complex objects.

2.1 Method

2.1.1 Participants. There were four groups of participants (total $n = 42$; see table 1 online—<http://dx.doi.org/10.1068/p5596>), including early-blind (EB— $n = 10$; 4M, 6F), late-blind (LB— $n = 12$; 7M, 5F), very-low-vision (VLV— $n = 10$; 5M, 5F; light perception and the ability to locate strong lights), and blindfolded-sighted (BS— $n = 10$; 4M, 6F) subjects with age range = 22–58 years and mean age, $M = 40.8$ years.⁽¹⁾

2.1.2 Stimuli and apparatus. The stimuli were complex 3-D wooden forms (without details) previously used in the study of haptic viewpoint in BS participants (Heller et al 2006). The tangible matching drawings are shown in figure 1. The wooden objects were birch and/or maple, sanded smooth and finished in a polyurethane varnish (see figure 2 for

Figure 1. Haptic pictures from experiment 1.

⁽¹⁾ M = male, F = female.

Figure 2. Wooden objects with details from experiment 2. The same objects were used without the details in experiment 1.

illustrations of the objects with details). The tangible drawings were produced on swell paper. Choice sets included four pictures, with one correct choice and three randomly selected pictures drawn from the same viewpoint.

2.1.3 Design and procedure. The experiment was a between–within design, with independent groups for visual status (LB, EB, VLV, BS), and repeated measures on the viewpoint of the tangible pictures (top, 3-D, frontal with converging lines). The six objects were presented in a random arrangement for each viewpoint, but viewpoint was blocked. The order of presentation of the viewpoints was randomized. Each subject was exposed to 18 trials and the task on each trial was to feel an object and match the correct picture to it. Further details about the method are in Appendix A.

2.2 Results and discussion

Performance in terms of the number of correct responses was slightly lower for the EB ($M = 79\%$ correct) and BS ($M = 81\%$ correct) participants, but higher accuracy was obtained for the VLV ($M = 86\%$ correct) and LB ($M = 94\%$ correct) subjects. The results can be seen in table 2 online. The LB subjects showed excellent accuracy, which was unexpected given the complexity of the pictures and the objects. Similar high accuracy was found overall for the three viewpoints (see table 2 online, $M = 85\%$ correct for top views, 87% correct for frontal views, and 83% correct for 3-D views).

An ANOVA on the number of correct responses (unweighted-means ANOVA) indicated that the effect of visual status was marginally significant ($F_{3,38} = 2.67$, $p = 0.06$). However, another ANOVA on the same variable reached significance when a weighted-means analysis (SYSTAT) was used ($F_{3,38} = 2.85$, $p = 0.05$). This was the only instance where a potentially meaningful disparity existed between the two types of analyses. An unweighted-means ANOVA on the effect of viewpoint on the number of correct responses failed to reach significance ($F_{2,76} = 0.7$, $p = 0.5$), but the interaction between viewpoint and visual status was highly significant ($F_{6,76} = 3.39$, $p < 0.01$). The simple effect of viewpoint was highly significant for the BS subjects, who did worse with 3-D pictures than the other views ($p < 0.01$), but not for the other groups of subjects (all $ps > 0.05$). Furthermore, the simple effect of visual status was not significant for top views ($F_{3,83} = 0.95$, $p = 0.4$). However, the simple effect of visual status was significant for the front views ($F_{3,83} = 4.2$, $p < 0.01$). The EB subjects had lower performance for front views ($M = 72\%$ correct) than the other participants, with their highest accuracy for 3-D views ($M = 85\%$ correct; see table 2 online).

The four groups of subjects showed relatively similar performance overall. Certainly, a lack of visual experience did not impede the EB subjects, since their overall performance in terms of accuracy was comparable to that of the BS participants. Of course, all groups of visually impaired subjects were faster than the BS. Note that overall matching performance was relatively high, especially for the LB (see table 2 online) subjects.

3 Experiment 2. Object detail and viewpoint effects

Viewpoint effects could vary with object discriminability (Hayward and Williams 2000) and surface details or parts (Rossion and Pourtois 2004; Tarr et al 1997). Consequently, in this experiment we examined the effect of the presence of small object details on the fronts of the objects on ease of picture matching. It was thought that increasing object complexity, by adding a detail, could alter performance. In many instances, the presence of object details may magnify viewpoint effects and improve performance. Moreover, in this experiment we attempted to determine if there were any relationships between the presence of details, viewpoint effects, and visual experience. If haptics provide a crude understanding of global shape (eg Revesz 1950), then one might expect lower performance for matching when the objects contain details. If visual experience were critical, then one should see lower performance by the EB subjects.

3.1 Method

3.1.1 *Participants.* The subjects were the same ones who participated in experiment 1.

3.1.2 *Stimuli and apparatus.* The stimuli included the six wooden objects that were used in the first experiment. An additional set of six identical objects was created, but differed in the addition of a small detail (bump) on the front surface of each. The detail was placed at the widest point. Half of the objects contained details and half did not (see figure 3).

There were six objects with details and six without per viewpoint, for a total of 36 trials per subject. The matching picture choice sets included the correct choice and three other randomly selected pictures, drawn from the same viewpoint for the target objects without details.

3.1.3 *Design and procedure.* The experiment was a between-within design, with independent groups for visual status (LB, VLV, EB, BS), with repeated measures on viewpoint of the tangible matching pictures (top, front, 3-D), and presence or absence of object detail. Each subject was exposed to all viewpoints in random order, with viewpoint blocked. The procedure was like that of the first experiment, with the only exception being the statement before the first trial to "...be sure to feel the wooden objects very carefully".

Figure 3. Haptic pictures with details from experiment 2.

3.2 Results and discussion

An ANOVA on the number of correct responses (unweighted-means ANOVA) revealed a significant effect of visual status ($F_{3,38} = 3.5, p = 0.025$), owing to higher performance by the LB subjects ($M = 89\%$ correct; see table 3 online). The VLV participants also had high performance levels ($M = 84\%$ correct). The EB ($M = 77\%$ correct) and BS ($M = 74\%$ correct) participants had similar, but lower accuracy. Mean scores were highest for the front views, and the main effect of viewpoint was highly significant ($F_{2,76} = 41.2, p < 0.001$). However, the interaction between viewpoint and visual status was also significant ($F_{6,76} = 4.6, p < 0.001$). The interaction derived from a different pattern of responses from the BS subjects. Their performance did not vary as a function of viewpoint ($p = 0.65$), but the blind groups all showed lower accuracy for the top-view pictures than the other viewpoints (all $ps < 0.02$; see figure 4). There was also a significant main effect of the object detail, with significantly higher scores when the detail was absent from the object ($F_{1,38} = 23.1, p < 0.01$). The interaction between visual status and detail was also significant ($F_{3,38} = 6.5, p < 0.01$). Tests of the

Figure 4. Mean number of correct responses as a function of visual status and viewpoint in experiment 2.

simple effects of the interaction showed that for the BS subjects the effect of detail was highly significant ($F_{1,38} = 12.3$, $p = 0.001$). None of the simple effects of the interaction between detail and visual status was significant for the visually impaired groups (all $ps > 0.40$). All of the other interactions with detail failed to reach significance (all $ps > 0.45$).

Some of the results were unexpected, especially the advantage of 3-D and front views for the blind participants (see figure 4). The presence of object details in this experiment may have magnified viewpoint effects. The EB subjects thought that they would do poorly with the 3-D views, and were all surprised when this was not the case. The 3-D shapes contain the top and front views, and thereby convey considerable useful information about the complex objects. The advantage of the LB and VLV subjects was consistent with earlier research (see Heller 1989; Heller et al 2002, 2003). The LB subjects were probably aided by the combined effects of early visual experience with pictures and increased haptic skill derived from experience using touch for pattern perception.

Object details were not especially salient in top-view drawings of the objects. The details were small in size. This could certainly contribute to the difficulty of top-view drawings. Moreover, the BS subjects tended to trace the left and right sides of the target objects when feeling them. This led many of them to fail to notice the detail on the front of the objects themselves. This is not an optimal strategy for obtaining form information, given very complex forms with details. The blind subjects were more likely to explore the forms in an exhaustive, rapid fashion, including feeling the fronts of the objects, and this aided them in generating representations of the objects.

4 Experiments 3–5. Viewpoint effects in drawings of a model house

The earlier experiments reported here used a set of forms that varied in familiarity. Some of them were probably like shapes that subjects would have some experience with (eg the snowman and finial), while others were abstract composite constructions, derived from simple geometric forms (cubes and spheres). The effects of object detail and viewpoint may have varied with the configurations involved and could be limited to similar stimuli. For example, the top view of a person's head may not be 'best' in terms of ease of recognizing the individual, nor would it be a canonical view for vision. Moreover, the details that were used in experiments 1 and 2 of the present study may not have been especially salient in the drawings or the objects, owing to their small size and/or smooth rounded configuration. Conceivably, this could explain the lower performance for top views. Consequently in the following experiments we used a model house, which is a configuration that is relatively familiar, but contains a number of clearly distinctive features that characterize each side (see Heller et al 1995). For example, one end of the house has a chimney and the other end is blank, one side has a window, and the front has a door (see figure 5). This earlier research with the model house showed that elevated views of the model were more difficult for all groups of subjects, but the perspective viewpoint manipulations were very coarse. Heller et al (1995) merely distinguished frontal from a mixture of various elevated views. The present experiments extended the research to include new participants and more systematic manipulations of viewpoint, including front views and elevated views.

In experiment 3 we examined frontal corner and side views. Some of the views in experiment 3 showed the house from the corner and some from a side. All views were frontal and not elevated. Subjects felt the model house and then had to match a perspective drawing to that view. It was expected that subjects would have more difficulty with corner views than side views, since they are more complex. If visual experience were necessary for interpreting very complex perspective drawings, one might predict lower performance for the EB participants in all three experiments. This is clearly

Figure 5. One of the authors (AMW) seated in front of the model house, in the position of a participant in experiment 3.

the case in experiment 4 where the views included 45° elevated corner and elevated side views. The elevated corner views should present special difficulty, owing to their complexity. The last experiment included top-view choices and pictures that involved elevated views and side views. On each trial, the subjects were asked to pick the picture choice that showed the house from an elevated side view or a top view. This final experiment was intended to determine if the EB participants could adopt these view-points, and discriminate between perspective drawings that depicted varying elevations.

4.1 General method

4.1.1 Participants. The subjects were thirty persons who were visually impaired and ten newly recruited BS subjects. Some of the blind subjects participated in the earlier experiments reported here but a number were new to the research. None had any prior experience with the model house used in the present experiments. All participated in experiments 3–5, in that order.

4.1.2 Stimuli and apparatus. The model house and experimental arrangement are shown in figure 5. The overall size of the model is about 15.5 cm by 12.7 cm (at the roof, including the chimney) with a height at the peak of the roof of 11.9 cm. the model was mounted on a turntable so it could be rotated upon a central axis. In addition, it was clamped in place on each trial to allow a stable stimulus for haptic exploration.

The standard positions of the house in experiment 3 included the four sides (front with door, back with window, right side with chimney, left side) and the four corners. Each position (four sides and four corners) was presented in a random arrangement within a trial block; there were two trial blocks, for 16 trials. The picture choices were drawn from a frontal position, at a distance of 50.8 cm from the house. When producing standard-choice drawings, the eye was level with the eave of the model house.

The tangible swell-paper pictures were presented in choice sets, with each including four pictures of the house: one was the correct choice, two choices were drawn with the house rotated $\pm 22.5^\circ$ from the correct position, and one picture was randomly chosen from other front or corner views of the house. We used 22.5° rotations, since smaller rotations were too difficult visually. The top line of figure 6 shows pictures of the four sides of the house and the second line shows the pictures of the four corners.

Figure 6. Frontal view drawings in experiment 3. The top row shows the pictures of the four sides of a house; the second row shows the drawings of the four corner views.

In experiment 4, the stimuli were all elevated views drawn from a 45° angle, either from a corner or side. There were four elevated-corner views drawn from all of the corners of the model house and four elevated side views. The picture choices included two trial blocks for each subject. One trial block involved elevated corner 3-D views, and the other included elevated side 3-D views, presented in balanced order. The views were explained for the subjects and the four choices on each trial included the view from each side (or corner) of the house (see figure 7).

Experiment 5 involved varying elevations of the house to be identified, and required participants to discriminate between pictures that were drawn from the correct side, but which differed in elevation. On each trial, the correct choice consisted of either an elevated side view or top view (bird's-eye view) of the model house (see figure 7). The correct view to be adopted was identified for the subject on each trial. Thus, for example, a participant was told that the correct choice on a given trial was a top view (or elevated side view, if appropriate). The top view was drawn in parallel projection, without foreshortening. The subjects were exposed to 4 trials with elevated side views and 4 trials with elevated top views as correct choices, in a completely random order, but not blocked by viewpoint. The task involved orienting the model so that one of the four sides faced the participants, twice each in a random order. On each trial, the picture choice set comprised the three pictures that corresponded to the appropriate side, including a side view, a top view, and a $+45^\circ$ elevated side view. A fourth choice was randomly selected from a depiction of one of the other sides. Participants were instructed to select the appropriate top view or elevated side view from the choices.

4.1.3 General procedure. The experiments were mixed-factor ANOVAs, with the between-groups variable being visual status (EB, LB, VLV, BS). In experiment 3, repeated measures were taken on viewpoint (corner versus side views), and trials (2). Experiment 4 had

Figure 7. Drawings of (a) the elevated side views from experiment 4; (b) corner views from experiment 4; (c) a top view from experiment 5.

two trial blocks corresponding to elevated side or elevated corner views. In the final experiment, participants were told to pick (select) the picture that showed the house from the correct elevation and the correct side.

The participants were exposed to the model at a particular position and asked to feel it and the four picture choices. They were to indicate which picture showed the house from the position that it faced. The subjects were instructed to feel all four choices before making a match and were told that they would be timed. However, they were instructed to try for accuracy and take as much time as they needed. Subjects were timed from their first contact with the house until they gave a matching response. Feedback on responses was not provided.

4.2 Results and discussion

The results of experiment 3 (see table 4 online) show somewhat lower accuracy for the EB participants ($M = 47\%$ correct), but higher accuracy was found for the LB ($M = 64\%$ correct), VLV ($M = 64\%$ correct), and BS ($M = 59\%$ correct) participants. However, an ANOVA on the number of correct responses yielded a non-significant effect of visual status on matching accuracy ($F_{3,36} = 1.6$, $p = 0.21$), but a highly significant effect of viewpoint ($F_{3,36} = 43.53$, $p < 0.001$). The effect of viewpoint derived from much better performance for the side views ($M = 70\%$ correct) than the corner views ($M = 47\%$ correct). A similar pattern of performance, as a function of viewpoint, was obtained for all groups of subjects. The other effects failed to reach significance (all $ps > 0.29$). The performance of EB subjects did not differ significantly from that of the others, indicating that visual experience is not needed for this picture perception task.

Touch yielded surprisingly good performance for this difficult task. For purpose of comparison, we tested an additional group using vision. Matching of the side views was clearly easier than of the corner views of the house for both vision and for touch. In comparison with touch (M overall = 58% correct), the advantages of vision (M overall = 83% correct) were present throughout, but were greater for the side views. The side-view pictures are far less complex, and corner views required subjects to estimate the relative proportions of the sides of the house in the pictures (and the house) in order to make their judgments.

In experiment 4 elevated side and elevated corner views drawn from a 45° angle were compared (see figure 7). Subjects performed better on elevated 3-D side views ($M = 85\%$ correct) than with elevated 3-D corner views ($M = 73\%$ correct; see table 5 online).

Mean percentages correct for the EB, LB, VLV, and BS subjects were 65%, 90%, 80%, and 80%, respectively. However, an ANOVA on the number of correct responses just failed to reach significance for visual status ($F_{3,36} = 2.7$, $p = 0.059$), but the effect of viewpoint reached significance ($F_{1,36} = 5.96$, $p = 0.02$). Moreover, the interaction between these variables was not significant ($F_{3,36} = 0.72$, $p = 0.55$). The relatively good performance on this task is probably related to the presence of distinctive details that helped subjects identify the appropriate viewpoints ($M = 90\%$ correct for LB subjects). For example, subjects could use the position of the chimney in drawings to help them solve the problem that was posed by turning the house so that the corner with the chimney faced them.

It was noteworthy that some EB subjects claimed that they thought that it was “funny” that they were told that they should imagine that the house was elevated at eye-level when a side view was depicted in experiment 3. These individuals did not initially understand why a picture should vary as a function of elevation. This was the motivation for the final experiment. Reduced experience with perspective drawings could lead to difficulties when a task required participants to discriminate between drawings from the side, from a 45° elevation, or from a bird’s-eye view.

The task in experiment 5 involved the experimenter identifying a particular elevated view (elevated side view or top view) and presenting the house with one side toward the subjects. The subjects were required to select the correct view from a set of picture choices. The participants were told that the correct choice on each trial was either a top view or an elevated side view, as appropriate. A correct match required that the subject identify the picture that showed the house in the appropriate orientation and discriminate between pictures of different elevations of the house at that position, that is, side view, $+45^\circ$ elevated side view, and top view.

The results showed somewhat lower performance by the EB participants ($M = 65\%$ correct; see table 6 online). An ANOVA on the number of correct responses showed that the effect of visual status was significant, owing to better performance by the VLV subjects ($M = 91\%$ correct) ($F_{3,36} = 3.2$, $p < 0.05$). A Newman–Keuls test on the means for the groups showed that the VLV participants had significantly better performance than the EB subjects ($p < 0.05$), but all other comparisons between the means failed to reach significance ($p > 0.05$). The effect of viewpoint reached significance, with higher mean scores for identifying the top views ($F_{1,36} = 7.8$, $p < 0.01$), but the interaction between visual status and viewpoint failed to reach significance ($F < 1$).

The VLV participants performed much better than the EB subjects, but this does not mean that visual experience is necessary for adopting perspective views. The mean number of correct responses by the EB subjects did not differ significantly from that of the BS subjects ($M = 80\%$ correct). The advantage of the VLV may derive from the combined benefits of visual experience and haptic skill. While the LB subjects (M overall = 70% correct) performed relatively poorly here on elevated views, it is possible that the methods of the present experiment were more likely to reveal viewpoint effects than experiment 4. Viewpoint was blocked in experiment 4, and this may have aided performance. Note, however, that the interaction between viewpoint and visual status failed to reach significance in experiment 5.

5 General discussion

The results of the present study suggest that visual experience is not necessary for understanding tangible perspective pictures of complex solid objects. This was shown by the similar levels of performance by the EB and BS subjects in experiments 1 and 2 reported here, and the overall respectable levels of performance for haptic perception. In addition, the results of experiments 3, 4, and 5 were consistent with this interpretation of the data, given the non-significant differences in performance between the EB and BS subjects.

The VLV and LB subjects were often more accurate and much faster than the BS subjects restricted to haptics. The advantage of the LB and VLV subjects in speed and accuracy is probably linked to their prior experience of using haptics for picking up spatial information, coupled with their earlier experience with pictures. There were instances of very high performance by the LB (experiments 1 and 4) and the VLV (experiment 5) subjects, exceeding 90% correct. The BS subjects lack haptic skill and the EB subjects lack experience with pictures.

Superior performance was found for side (frontal) views, especially when compared with corner views in experiment 3. Elevated side views of the model house were easier for the subjects in experiment 4 than elevated corner views. Matching accuracy was lower for the adoption of top views in experiment 2 for the blind subjects, but not in experiment 5. And this result suggests that the utility of top views depends upon stimulus characteristics. The effect of viewpoint was contingent upon the presence and salience of object details. Overall, the pattern of results of the present experiments suggests that any differences that appeared between the EB and the other subjects are probably explainable in terms of differences in experience with pictures. However, this experience need not be specifically visual in nature.

The results of the second and third experiment are consistent with the notion that haptic pattern recognition may be influenced by viewpoint, and this may be altered by the nature of the stimuli (eg Tarr et al 1998). The visually impaired subjects in experiment 2 all performed better on front and 3-D views than top views. Top views and some other types of elevated views may be easier for subjects when the object is relatively simple and details are especially salient, as in the features (peak of roof, chimney, door, window) of the model house (experiments 3–5). A great deal more needs to be done in this area, since the effects of detail on haptic viewpoint effects are complicated and vary with the stimuli. In vision, for example, the top view of a person is not canonical and might not support the recognition of individuals. Front views or 3-D views might be more suitable. Unfortunately, we do not yet have enough information about the ‘best’ views for depicting objects in haptics and for blind people.

The results of these experiments have applied implications and suggest optimism regarding the value of complex perspective drawings for blind people. One clear implication is that graphics for blind people can make effective use of 3-D representations. One should not automatically rule out these sorts of perspective views on the assumption that they may be too difficult. Complex 3-D views, even when they involve elevated corner views, may take more time to explore via touch, but they are comprehensible. These views may not be optimal forms of representation for some maps, for example, but can be very useful for other sorts of tangible pictorial displays.

Finally, it is important to emphasize that perspective is a higher-level perceptual and cognitive achievement (Panofsky 1991). There are certainly some visually impaired and totally blind individuals with exceptional drawing skills (see Kennedy and Juricevic 2006). Most individuals, whether sighted or blind, benefit from instruction in perspective before they are able to correctly produce these sorts of drawings. Thus, some EB subjects in experiments 3–5 erroneously speculated about the utility of peripheral vision, and thought that peripheral vision would allow a sighted person to see around the sides of this object when this was not possible. Similarly, in earlier research (Heller et al 2002), some EB subjects asked if a front view would allow a sighted person to see anything beyond the closest point of a geometrical solid (eg hexagonal prism). Obviously, instructional variables matter and future research with EB individuals should take this into consideration. Nonetheless, the EB subjects can clearly benefit from exposure to tangible perspective drawings and some of them showed relatively high levels of performance.

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Appendix A. Methodological details

Participants. Subject characteristics are shown in table 1 online. Some of the participants served in all of the experiments reported here, but some of those in experiments 3–5 were new to the research. The visually impaired participants were recruited from Charleston, Champaign/Urbana, Crystal Lake, Bloomington, and Springfield, Illinois. The EB subjects all lost sight in the first year of life, with the exception of one person who lost sight before the age of 2 years. VLV participants had light perception, but were not able to see much more. All of them could see the direction of strong light sources, but the few with minimal pattern perception were also Braille readers and used long canes for mobility. The LB subjects all lost sight after the age of 2 years, and most were unable to see light. If they could see light, they were unable to provide directional information for strong light sources. The LB sample was larger than the other groups, because two persons who had recently had VLV lost their remaining light perception, but were not aware of this when the research was scheduled. For example, one person thought that she still had light perception, but she could not tell whether the very bright room lights were on or off. The BS participants were recruited from among faculty, staff and students at Eastern Illinois University. The subjects in the first experiment also participated in experiment 2.

Stimuli in experiments 1 and 2. The stimuli were a lighthouse, snowman, ball with egg (orb-egg), finial, large-medium-small cube (in size order, bottom up), and large-small-medium cube. The hardwood objects ranged in size from 14.4 cm in height (lighthouse) to 10.8 cm high (large-medium-small cube).

Prior to testing, the subjects were all asked to feel the wooden objects and draw them with a raised-line drawing kit. This procedure was adopted to familiarize the blind subjects with the notion that complex objects could be represented in a tactile 2-D form. The same procedure was adopted for the BS subjects. Feedback on this task was not given, but the subjects were asked to try to show that the objects were ‘solid’ in their drawings, if they could. Subsequently, subjects were exposed to the objects, one at a time. They were given instructions on the appropriate viewpoint by telling them about it and by moving their hands to the objects for further clarification. For the front views, participants were told that, when drawn, the objects were held up so that the bottom was at eye-height, and the tops of the objects were higher. Some EB participants remarked that they thought that it was “odd” and “funny” that we commented on the height of the objects when drawing them. This point is taken up again in the manuscript. Then the experimenter moved one of their hands from face towards a sample object (eg a cylinder). For the top views, the participants were instructed that the views were from directly above, and their hands were moved down from above to the tops of the objects. For the 3-D perspective viewpoints, participants were told to imagine that they could look down at an angle at the objects from where they were sitting. The experimenter moved their preferred hands from near their eyes to the object, and they were instructed that they could see the tops and fronts of the objects from this viewpoint. They were told to feel the object and then feel the four pictures below each object. They were permitted to feel the objects and pictures for as long as they wished before they made a match to indicate which object was depicted. They were then instructed to feel all four picture choices before making a match. Subjects were told that they would be timed, but were to try for accuracy. In addition, they were allowed to repeatedly feel the solid object while feeling the matching pictures. This method was adopted to minimize the memory load involved. Subjects were instructed that they could use one or both hands, as they wished.

Participants were not allowed to move the solid target object, since it was fixed in place. Feedback on performance was not given.

Stimuli for experiment 2. For the lighthouse, the detail was placed in the front at the greatest circumference of the major part, not the base (see figures 2 and 3). The details were comprised of toy 'axle rods', with a 0.6 cm diameter and they extended 0.5 cm from the object's surface; the tangible detail consisted of a wheel-like projection. The detail on the lighthouse projected outward 0.95 cm from the front surface to ensure that it would be visible from a top view. The dowel portion of the axle rod was glued into a hole drilled into the widest part of each object.

For the target objects without details, half of the picture choices contained details and half did not. In the case where the target object contained a detail, two of the four choices contained a detail and two did not. When the target contained a surface detail, two of the choices included the identical global form: one contained the detail (the correct choice) and one did not. The matching arrays were not identical when the target objects contained a detail and when they did not. One might expect that duplicating the global form would reduce task difficulty, since the odds of locating the correct shape by chance should be higher on those trials. Conceivably, this could complicate any comparisons between the detail and no-detail conditions. However, we adopted this procedure for a couple of reasons. First, we wanted to ensure that subjects were not simply selecting their choices in terms of whether or not the correct choice contained a detail. Furthermore, we wanted to be sure that the subjects really understood the pictures. Also, we did not want subjects to notice the pattern duplication, and we were concerned that they might notice this if all trials were identical, that is if there were two versions of the correct global target form on all trials. Consequently, we did not have the same matching configuration for the targets with and without object details.

Procedure in experiment 2. Half of the target objects contained the single object detail on their front face, but half did not. The sequence of presentation of the stimuli within each block of viewpoint trials was randomized. As in experiment 1, subjects were not given feedback on performance. Participants were not told about the presence of object details, because we wanted to determine if they would spontaneously discover their presence. Future research should explicitly manipulate this instructional variable, and perhaps the location of the details. In the present study, we were interested in discovering if exploration might differ between blind and BS subjects.

Experiments 3–5

Participants. The EB subjects (4M, 6F) were all blinded before the age of 2 years. The LB (7M, 3F) participants had no useful vision or were totally blind, and all lost their sight after the age of 2 years. The VLV subjects (6M, 4F) had light perception that permitted them to see the direction of strong light sources, as in the earlier experiments reported here. The new experimentally naive BS subjects (6M, 4F; mean age = 41.7 years) were recruited on a college campus, and included faculty, staff and students (age range = 21–63 years). Experiments 3–5 were conducted more than 1 year after experiments 1 and 2.

Design and procedure. All subjects were exposed to the model house and asked to feel it and try to identify it. This was relatively easy and all but one said it was a model house, or a birdhouse. Subsequently, the subjects were asked to imagine that they were standing in front of the model, facing the door and asked to describe what one could 'see' from that position. The house was then rotated gradually, in a clockwise direction and at each pause the subjects were asked what one could see from that position. This continued until the side of the house with the chimney was facing the subjects. Then they were asked what one could see of the house from the position they were in with respect to the model. This was asked to ensure that all the blind participants understood

the notion of a viewpoint. The subjects were asked what one could see from the front, from above, as if they were a bird looking straight down upon the roof of the house, and from a corner. When facing a corner, the subjects were asked to imagine what could be seen from the front and when elevated at a 45° angle. The angle of regard and distance were demonstrated, for this elevated corner view, with a large plywood triangle. The subjects were asked to feel the wooden triangle and the appropriate vantage point was indicated to them. A few of the EB participants said that, when facing the side of the house with the chimney, they thought that one could “see” the window on the (now) right side, even though that side of the house could not be visible to them. When asked, these persons said that they had heard that people with sight had peripheral vision, and they thought that peripheral vision would allow sighted persons to see around a corner. The experimenter then asked these individuals if they thought that a sighted person could see an object through the wooden table surface, for example. All said that this was not possible. No further verbal feedback was given.

The subjects were asked to draw tangible pictures of the house from a variety of views, using a Swedish raised-line drawing kit. These views included a front view, a top view, a corner view, an elevated side view, and an elevated corner view. This procedure was adopted to familiarize subjects with the viewpoints that were used in the experiment. Feedback on the drawings was not given.

Appendix B. Results: ANOVAs on time and report of visual group

Experiment 1. An unweighted-means ANOVA on time scores yielded a highly significant effect of visual status, owing to much faster performance by the VLV participants and slower performance by the BS participants ($M = 60.3$ s, $F_{3,38} = 7.9$, $p < 0.001$). On average, the VLV subjects were twice as fast as the BS participants. The effect of viewpoint was significant ($F_{2,76} = 18.8$, $p < 0.001$), because of slower performance with 3-D views. However, there was also a significant interaction between viewpoint and visual status ($F_{6,76} = 2.7$, $p = 0.019$). The interaction derived from the greater sensitivity of the BS subjects to viewpoint, since, unlike the visually impaired participants, they responded faster to the top views ($M = 48.3$ s) than the front views ($M = 64.5$ s) or the 3-D views ($M = 68.1$ s).

The main effect of object was significant ($F_{5,190} = 22.6$, $p < 0.001$), but the interaction between object and viewpoint was also significant ($F_{10,380} = 10.8$, $p < 0.001$). Overall, response latencies were shortest to the orb-egg. The simple effect of viewpoint did not matter for the lighthouse ($F = 1.0$), but was significant for all of the other objects (all $ps < 0.05$).

The blind subjects engaged in a haptic behaviour that was analogous to visual projection for the top views. In an attempt to determine which contours covered each other, they would hold their fingers at the tops of the rounded forms and then attempted to trace the contours ‘straight’ down from their tops to their bottoms to determine the maximum extent of components of the objects. When asked, they said that they counted circles when matching the pictures against the standards. Thus, they attempted to use touch to ascertain what might be ‘visible’. This method was not very useful for one aspect of the snowman, since the wider extent of the belly was not visible monocularly at the viewing distance used to generate the depiction.

Experiment 2. An unweighted-means ANOVA on time scores showed a significant effect of visual status ($F_{3,38} = 14.3$, $p < 0.001$), with the blind subjects responding much faster than the blindfolded sighted participants. The results of a weighted-means ANOVA were basically the same. The main effect of viewpoint was also significant ($F_{2,76} = 12.5$, $p < 0.001$), with slower performance for the 3-D views. However, there was significant interaction between viewpoint and visual status ($F_{6,76} = 5.4$, $p < 0.001$). The interaction

derived from much slower performance for the 3-D views than the other views for the BS subjects (see table 3 online). The visually impaired subjects did not show substantially slower performance for the 3-D views. There was also a significant effect of detail ($F_{1,38} = 16.6$, $p < 0.001$). However, the interaction between viewpoint and detail was significant ($F_{2,76} = 7.8$, $p < 0.001$). The subjects were slower when the object contained a detail, but not for the top views. All of the interactions between visual status and detail failed to reach significance (all $ps > 0.22$).

A few of the visually impaired subjects, especially the EB subjects, objected to the front view picture of the lighthouse while feeling it, and said that it could not be a picture of that object. They stated that the base of the wooden lighthouse itself was curved. The front view haptic picture of the lighthouse had no curves, unlike the 'real' lighthouse, and so it was rejected as a potential match.

Experiments 3–5. An ANOVA was performed on time scores and yielded significantly slower performance by the BS participants in experiment 3 ($F_{3,36} = 3.2$, $p < 0.05$). The main effect of trials was significant ($F_{1,36} = 28.7$, $p < 0.01$), as was the effect of viewpoint ($F_{3,36} = 30.96$, $p < 0.001$). Subjects were faster on the second trial block ($M = 73.2$ s) than the first trial block ($M = 92.2$ s), and faster for side views. However, there was also a significant interaction effect between trials and viewpoint. All of the tests of the simple effects of this interaction were significant (all $ps < 0.01$). While subjects were faster for both views on the second trial, the impact of practice was much greater for the corner views than for the side views.

In experiment 4, time scores indicate faster response times for the elevated side views ($M = 64.8$ s) than for the elevated corner views ($M = 81.1$ s). The advantage for the side views reflected their relative ease compared to the corner views in terms of response latency and accuracy. The blindfolded sighted subjects were somewhat slower than the others. However, a second ANOVA on time scores showed that the effect of visual status failed to reach significance ($F_{3,36} = 2.45$, $p = 0.08$), but the effect of viewpoint was highly significant ($F_{1,36} = 13.8$, $p < 0.001$) because of shorter latencies for side views. The interaction between viewpoint and visual status failed to reach significance ($F < 1$).

For experiment 5, an ANOVA was run on time scores and yielded a non-significant effect of visual status ($F_{3,36} = 2.1$, $p = 0.12$). However, the effect of picture viewpoint was significant ($F_{1,36} = 20.96$, $p < 0.001$), with faster responses for top views ($M = 49.5$ s) than for elevated side views ($M = 62.2$ s). The BS participants were the slowest of all of the groups ($M = 70.0$ s) and the VLV participants were the fastest ($M = 43.8$ s).

Visual data and analyses. To get a more complete idea of task difficulty, a separate group of naive undergraduate sighted subjects ($n = 10$; 4M, 6F) was exposed to the procedures of experiment 3, but they used normal vision. Between trials, a foam board panel blocked the view of the apparatus. Performance was nearly perfect for the side views of the house (see table 4 online), but a significantly lower mean number of correct responses was obtained for the corner views ($F_{1,9} = 24.9$, $p < 0.001$). In addition, the sighted subjects were significantly faster for the side views ($M = 4.1$ s; $SD = 1.49$ s) than the corner views ($M = 6.39$ s; $SD = 2.65$ s) ($t_9 = 4.4$, $p < 0.01$). While visual performance was certainly better and faster than touch, at least one of the visually impaired subjects had a higher number of correct responses than the average number shown by the sighted subjects using vision. This VLV individual had perfect performance in terms of accuracy. The pattern of results for vision was consistent with that obtained for touch.

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