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Haptic object recognition is view-independent in early blind but not sighted people

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Abstract

Object recognition, whether visual or haptic, is impaired in sighted people when objects are rotated between learning and test, relative to an unrotated condition, i.e., recognition is view-dependent. Loss of vision early in life results in greater reliance on haptic perception for object identification compared to the sighted. Therefore, we hypothesized that early blind people may be more adept at recognizing objects despite spatial transformations. To test this hypothesis, we compared early blind and sighted control participants on a haptic object recognition task. Participants studied pairs of unfamiliar 3-D objects and performed a two-alternative forced-choice identification task, with the learned objects presented both unrotated and rotated 180° about the y-axis. Rotation impaired the recognition accuracy of sighted, but not blind, participants. We propose that, consistent with our hypothesis, haptic view-independence in the early blind reflects their greater experience with haptic object perception.

Keywords

shape; rotation; touch

Introduction

Haptic exploration allows the acquisition of information from all surfaces of a three-dimensional (3-D) object, including those that are visually occluded, thus enabling the observer to fully process and represent its structure (Klatzky, Lederman, & Metzger, 1985; Lederman & Klatzky, 1987). Therefore, one might assume that haptic object recognition would be unaffected by a change in orientation, i.e., it would be view-independent. However, a number of studies have shown that haptic recognition of 3-D objects is significantly impaired if the objects are rotated between encoding and recognition phases and is therefore

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Conflict of interest
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view-dependent (Craddock & Lawson, 2008; Lacey, Peters, & Sathian, 2007; Lawson, 2011; Newell, Ernst, Tjan, & Bülthoff, 2001; reviewed by Lacey & Sathian, 2014). For unfamiliar objects, view-dependence characterizes both visual and haptic recognition (Newell et al., 2001; Lacey et al., 2007). Even haptic recognition of *familiar* objects, which might be expected to be less affected by orientation changes, can be impaired if the objects are rotated far enough from the so-called canonical or prototypical view (Theurel, Frileux, Hatwell, & Gentaz, 2012; Woods, Moore, & Newell, 2008). The view-dependence of haptic object recognition suggests that, like vision, the haptic system prefers a viewer-centered (as opposed to object-centered) reference frame for representing stimuli (Wraga, Creem, & Proffitt, 1999; Turnbull, Carey, & McCarthy, 1997). This might hamper the ability to represent relationships between the component parts of an object, thus making it difficult to imagine the object's structure after its orientation has changed (Logothetis & Sheinberg, 1996).

The role of visual experience in haptic viewpoint-dependence for 3-D objects is not completely clear (see Heller, McCarthy, & Clark, 2005 for a review). On the one hand, studies investigating the ability of blind and sighted participants to draw learned 3-D objects (Heller, Kennedy, & Joyner, 1995; Heller et al., 2002) or to match them to corresponding 2-D raised-line drawings (Heller et al., 2002; 2006; 2009) suggest that visual experience is not necessary to correctly recognize or represent objects in different orientations. Similarly, Theurel et al. (2012) found that the congenitally blind recognized simple 2-D shapes equally quickly whether they were rotated or not, while the sighted were slower in the rotated condition. However, on tasks involving mental rotation in order to match haptically perceived shapes, one study found that the congenitally blind were both slower and less accurate than the sighted (Güçlü, Celik, & Ilci, 2014) while another found the reverse (Rovira, Deschamps & Baena-Gomez, 2011). Since haptic recognition is impaired by the reduced dimensionality of 2-D compared to 3-D stimuli (Klatzky & Lederman, 2011), the 2-D shapes and picture-matching tasks used in the earlier studies of mental rotation are not readily comparable to 3-D object recognition tasks. One study showed that early- and late-blind individuals were better than the sighted at 3-D object discrimination, while the congenitally blind did not differ from the sighted (Norman & Bartholomew, 2011), suggesting that visual experience and haptic experience each confer some advantage. But although the objects in this study were presented in random orientations, the crucial effect of orientation change itself was not addressed. Landau (1991) reported that a congenitally blind child was view-independent at three years old and performed comparably to sighted children, suggesting that visual experience is not necessary for the emergence of view-independence, but this was a case-study of a single child.

Thus, it is not firmly established whether the blind and sighted are equally susceptible to changes in orientation in haptic 3-D object recognition. One idea is that the blind simply have more experience than the sighted in haptic exploration of objects, which might lead to superior ability at spatial transformations. Alternatively, the blind and sighted might employ qualitatively different haptic imagery processes. Either of these possibilities might enable the blind to perform better than the sighted across changes in object orientation, regardless of whether they are better at haptic perception overall. In the present study, we used a two-alternative forced-choice (2AFC) haptic object recognition task, in sighted and early blind participants, to test the hypothesis that the blind are less susceptible to orientation changes. We used unfamiliar 3-D objects to minimize effects associated with categorization or verbal labelling. These novel objects were equally unfamiliar to blind and sighted participants. Participants were asked to learn two sequentially presented objects on each trial. At test, the objects were presented either in the original orientation or rotated 180° about the y-axis and participants reported whether each was the first or second object in the learned pair.

Results

To test whether the data were normally distributed, we obtained skewness statistics for the unrotated and rotated conditions in each group and converted these to z-scores; skewness z-scores greater than 1.96 would indicate a significant departure from normality (Field, 2009). Where this occurred, we confirmed the result with a non-parametric test.

The task was a 2AFC, therefore the chance level of performance was 50%. Performance was significantly above chance, in both the unrotated (mean ± s.e.m.: blind 74% ± 3%, t_{11} = 7.73, $p < .001$; sighted 78% ± 4%, t_{10} = 7.12, $p < .001$) and rotated (blind 71% ± 2%, t_{11} = 8.34, $p < .001$; sighted 64% ± 3%, t_{10} = 4.70, p = .001) conditions (all skewness z-scores < 1.96).

A repeated-measures analysis of variance (RM-ANOVA: within-subject factor: orientation, unrotated vs. rotated; between-subject factor: visual status, blind vs. sighted) showed that object rotation significantly reduced recognition accuracy ($F_{1,21}$ = 11.89, p = .002) but there was no significant difference overall between the blind and the sighted ($F_{1,21}$ = .23, p = .64). However, the crucial result for our hypothesis was the significant interaction between visual status and orientation ($F_{1,21}$ = 4.99, p = .04); post-hoc t tests (Bonferroni-corrected using α = .025) showed that rotation significantly reduced recognition accuracy in the sighted (t_{10} = 3.57, p = .005), but not the blind ($t_{11} < 1$, p = .35) (Figure 1).

To account for potential differences in the baseline performance between the two groups, we also compared the percentage change in accuracy when objects were rotated using the formula [(unrotated score–rotated score)/unrotated score]*100. This comparison showed that the blind were significantly less susceptible to the effect of rotation than the sighted ($F_{1,23}$ = 5.68, p = .03), averaging a drop in performance of 2.7% ±4.1 compared to a mean decline of 16.3% ±3.9 in the sighted. Although the sighted group's skewness z-score for percentage change was 2.9, indicating a significantly non-normal distribution, a non-parametric Mann-Whitney test confirmed the RM-ANOVA result that the rotation effect was significantly smaller in the blind than the sighted (median: blind 6.4%, sighted 11.8%; U = 34.0, Z = −1.97, exact p = .049). Group means and individual percentage changes are shown in Figure 2, from which we can also see that, while some blind participants actually improved in the rotated condition, none of the sighted participants did.

Discussion

In this study, we compared early blind and sighted control participants to test whether visual experience affects haptic view-dependence. As predicted, the sighted group was haptically view-dependent, replicating previous findings (Craddock & Lawson, 2008; Lacey et al., 2007; Lawson, 2011; Newell et al., 2001), but the early blind group was view-independent. There was no overall difference between blind and sighted participants – this may reflect the fact that the novel objects used here were equally unfamiliar to both groups but is also in line with previous studies (e.g., Norman & Bartholomew, 2011) given that our blind group was predominantly congenitally blind. Further, in our previous study using objects of the type used here, sighted participants exhibited within-modal recognition performance that did not differ significantly between vision and touch (Lacey et al., 2007). The critical hypothesis, however, is not that haptic perception is better in the blind than the sighted *per se*, but that their greater haptic experience enables them to deal with changes in orientation better than the sighted: this hypothesis was supported. We should note, however, that the objects used in the present study do not require fine-grained haptic shape perception. A task involving changes in orientation for objects distinguished only by subtle differences in curvature or curvature gradients might reveal view-dependence for both blind and sighted.

There are several potential factors that may explain a difference in view-dependence between blind and sighted individuals, the most intuitive being differing expertise in haptic exploration/recognition. Optimal recognition performance is determined by accurate matching of the information perceived during the test phase with the stored representations of the objects encoded during the study phase. If the orientation of the object is changed between study and test, this process can be disrupted because there is a mismatch between the perceived object and its stored representation. Blind individuals gain a considerable part of their knowledge of the surrounding environment through haptic information, translating into behaviorally observable advantages (e.g., Afonso, Blum, Katz, Tarroux, Borst, & Denis, 2010; Norman & Bartholomew, 2011; Sunanto & Nakata, 1998; although see Crabtree & Norman, 2014). Presumably, their reliance on haptic cues facilitates the construction of object-centered representations that are stable across spatial transformations, resulting in view-independent performance. Unlike blind people, sighted people rarely rely exclusively on haptic cues to recognize objects in their everyday life (Klatzky, Loomis, Lederman, Wake, & Fujita, 1993), thus possibly limiting their ability to haptically recognize 3-D objects across spatial transformations.

The blind and sighted might also have differed in their use of haptic exploratory procedures (EPs), specialized hand movements that extract specific information about an object, for example contour-following for shape or lateral motion for texture (Lederman & Klatzky, 1987). However, as judged by the experimenter administering the task, our blind and sighted participants manipulated the objects in comparable ways, principally contour-following by moving their fingers over the object rather than simple enclosure. It is currently unclear whether there are systematic differences in EPs between the blind and sighted. Withagen et al. (2013) found that age was a more important factor than visual status, EPs becoming more efficient in adults than children, while Rovira et al. (2011) found that, for 2-D raised-line patterns, the blind were more likely to use lateral motion while the sighted needed to use contour-following. On balance, we conclude that differences in EPs are unlikely to account for the observed difference in view-dependence.

Finally, mental imagery processes could conceivably contribute to the observed differences between groups. Typically, determining whether two items with different spatial orientations correspond to the same object results in response times proportional to the angular distances to be computed (Shepard & Metzler, 1971). Analogous patterns of performance have been observed for objects presented visually and haptically (Carpenter & Eisenberg, 1978; Marmor & Zaback, 1976), and similar brain regions near the intraparietal sulcus are active during both visual and tactile mental rotation (Prather, Votaw & Sathian, 2004), thus suggesting that mental rotation processes are shared across modalities. Further, mental rotation of tactile stimuli appears to operate in a reference frame determined by multisensory convergence rather than being purely hand-centered (Prather & Sathian, 2002). Individuals differ in their ability to spatially transform mental images depending on their preference for either object or spatial visual imagery (Blazhenkova & Kozhevnikov, 2009); these imagery preferences have also been demonstrated in the haptic modality (Lacey, Lin & Sathian, 2011). Hollins (1985) showed that the longer an individual had been blind, the more complex images they were able to construct and the less strictly pictorial their imagery became. Although the task used by Hollins (1985) did not test mental rotation, the results suggest that imagery in the early blind might be more of the spatial rather than object type, thus favoring view-independence. It is worth noting here that, in the sighted, spatial imagery is implicated in haptic perception of unfamiliar objects such as those used in the present study, whereas visual object imagery is more important for familiar objects (Deshpande, Hu, Lacey, Stilla, & Sathian, 2010; Lacey, Flueckiger, Stilla, Lava, & Sathian, 2010; Lacey, Stilla, Sreenivasan, Deshpande, & Sathian, 2014). It would be worthwhile for future studies to further investigate imagery style preferences in blind individuals and their behavioral consequences for haptic perception.

In summary, we show that the sighted are haptically view-dependent, in accordance with earlier studies, while the blind are view-independent. We suggest that the greater experience that the blind have with haptic perception improves their ability to deal with spatial transformations. Further work is needed to assess the impact of late vision loss and of individual differences in imagery preferences.

Materials and Methods

Participants

Twelve early blind participants (6 female; see Table 1) and 11 age-matched sighted controls (7 female) participated in the study. The mean age (±s.d.) of blind and sighted participants was 44 years (±15) and 43 years (±17) respectively. Three blind participants had minimal residual light perception, but were not able to localize light sources; none had form perception. Ten of the 12 blind participants were congenitally blind; the other two had lost form vision by age 4. All participants were right-handed as assessed by the validated subset of the Edinburgh Handedness Questionnaire (Raczkowski & Kalat, 1974).

All participants gave informed consent prior to the study and received monetary compensation for their participation. For the blind group, either Braille versions of the consent documents were provided or the experimenter read the forms aloud to the participant prior to signature. All procedures conformed to the Declaration of Helsinki and were approved by the Emory University Institutional Review Board.

Materials

We selected twenty objects from the set used in Lacey et al. (2007) to make ten pairs. Each object was made from six smooth, rectangular wooden blocks (1.6 × 3.6 × 2.2 cm), glued together in varying relative positions and orientations; the resulting objects were 9.5 cm high, with the other dimensions varying according to the arrangement of the component blocks. We chose these objects because they are complex (see example in Figure 3); equally unfamiliar to the blind and sighted – so that verbal labeling and facilitating effects due to canonical presentation/representation were unlikely (cf. Lederman, Klatzky, Chataway, & Summers, 1990; Theurel et al., 2012; Woods et al., 2008); and lacked distinctive textural features (cf. Newell et al., 2001; Withagen et al., 2013) that could have served as cues for changes in orientation. Lacey et al. (2007) reported that, for such objects, normally sighted individuals show viewpoint-dependence in both visual and haptic object recognition.

Procedure

During the encoding phase, participants haptically learned two objects, sequentially presented and identified as Object 1 and Object 2, for 10 seconds each. The order of the two to-be-learnt objects within each pair was counterbalanced across the participants and the ten pairs were presented in pseudorandom order. Each object was placed in the participant's hands, which were behind an opaque cloth screen, along its elongated z-axis (Figure 3). Participants were instructed to explore all around the objects and to remember their shape; they were told to keep each object in exactly the same orientation as given to them, and not to rotate or otherwise manipulate them. This was demonstrated to each participant using an example object not used in the actual experiment. The demonstration was visual for sighted participants. For blind participants, the example object was placed into their hands and the experimenter showed them what hand/object movements were impermissible. Compliance with these instructions was verified visually by the experimenter. Rare instances of accidental rotation were corrected by the experimenter gently pushing the object immediately back into the correct position and reminding the participant that such movements were not allowed. During the test phase, which immediately followed the encoding phase, participants were given each object one at a time, randomly presented either in the same orientation as during encoding, or rotated by 180° about the y axis (Figure 3). Participants were asked to report whether the object was the first or second in the pair they had learned (2AFC), with no time constraints, but were not told that the objects would be rotated. Thus, participants had to make four discriminations for each pair of objects (Object 1, rotated and unrotated, and Object 2, rotated and unrotated) and for the ten object pairs there were therefore 40 trials in total, 20 rotated and 20 unrotated.

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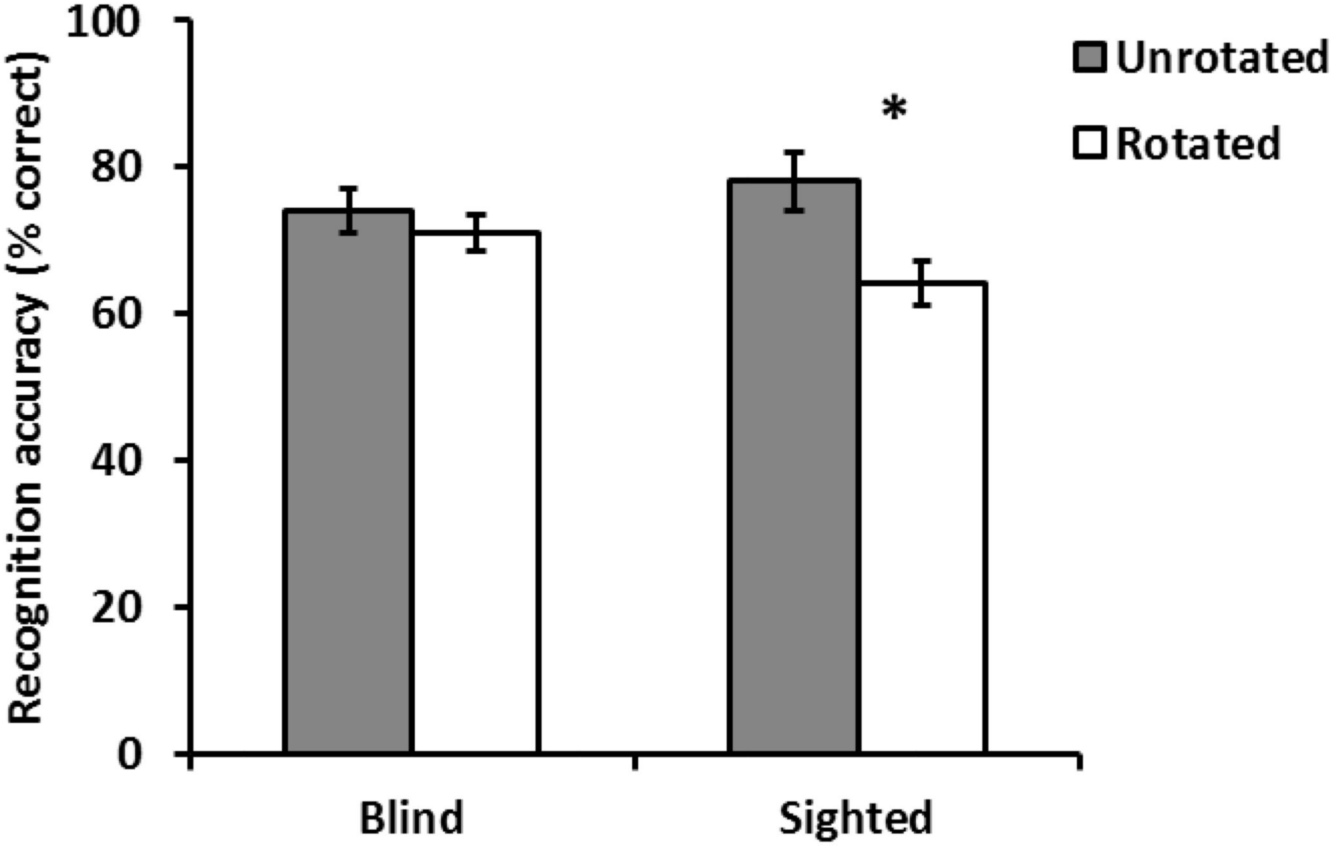

Figure 1.

Rotation significantly reduced recognition accuracy in the sighted but not the blind (error bars = s.e.m.; * = significant).

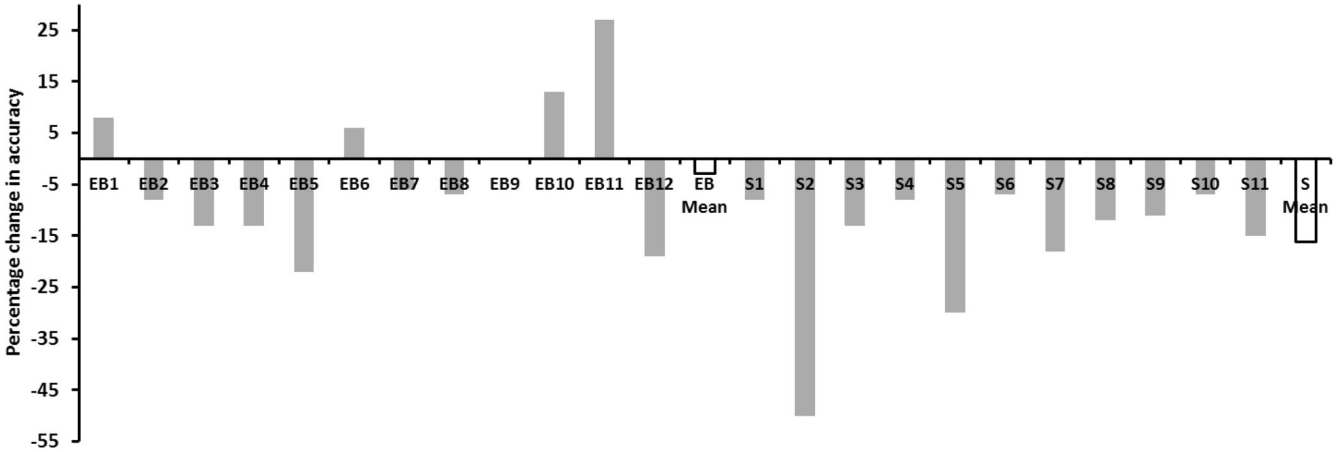

Figure 2.

Percentage change in recognition accuracy when objects were rotated, plotted by participant with group means also shown (EB = early blind; S = sighted).

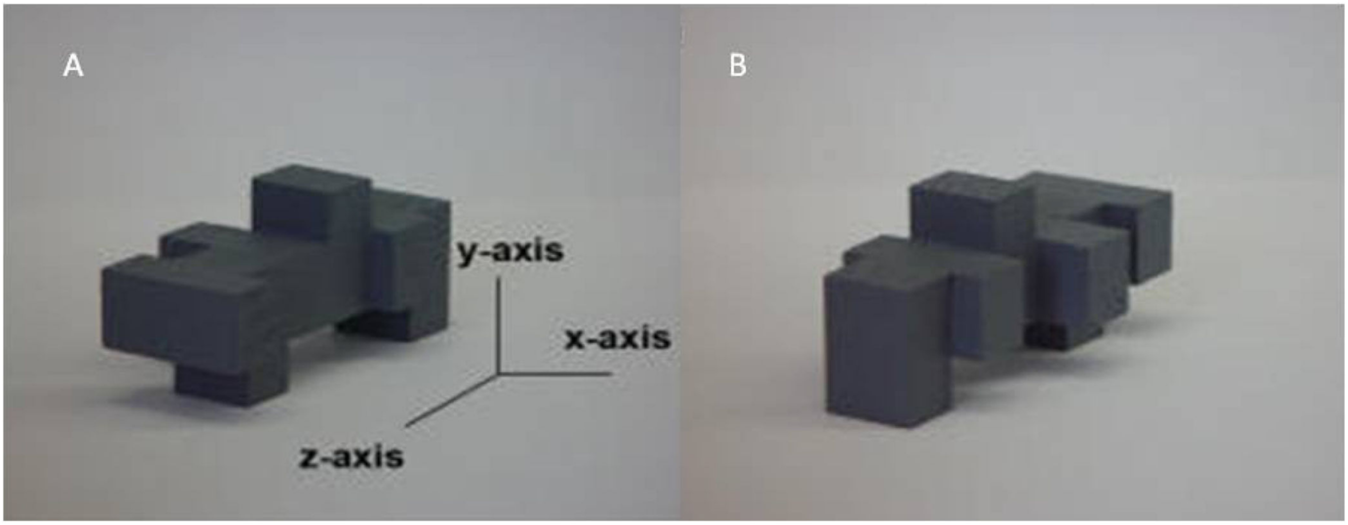

Figure 3.
Example object in (A) the original orientation and (B) rotated 180° about the y-axis (modified from Lacey et al., 2007).

Table 1

Demographic and clinical data for the blind participants.

Code	Gender	Age	Etiology	Form vision	Light perception
B1	F	50	Congenital glaucoma	No	No
B2	M	35	Retinal damage	No	No
B3	F	61	Retinopathy of prematurity & optic nerve atrophy	No	Until 18 yrs.
B4	M	44	Retinopathy of prematurity	No	No
B5	F	22	Optic nerve hypoplasia	No	No
B6	M	35	Retinopathy of prematurity	Right eye only & only in childhood	Yes
B7	F	26	Leber’s congenital amaurosis	No	Yes
B8	F	60	Retinopathy of prematurity	No	No
B9	M	48	Leber’s congenital amaurosis	No	Yes
B10	F	30	Optic nerve hypoplasia	No	No
B11	M	70	Unknown	Until 4 yrs.	No
B12	M	50	Congenital glaucoma	Until 4 yrs.	No