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Differences between early-blind, late-blind, and blindfolded-sighted people in haptic spatial-configuration learning and resulting memory traces

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Abstract. The roles of visual and haptic experience in different aspects of haptic processing of objects in peripersonal space are examined. In three trials, early-blind, late-blind, and blindfolded-sighted individuals had to match ten shapes haptically to the cut-outs in a board as fast as possible. Both blind groups were much faster than the sighted in all three trials. All three groups improved considerably from trial to trial. In particular, the sighted group showed a strong improvement from the first to the second trial. While superiority of the blind remained for speeded matching after rotation of the stimulus frame, coordinate positional-memory scores in a non-speeded free-recall trial showed no significant differences between the groups. Moreover, when assessed with a verbal response, categorical spatial-memory appeared strongest in the late-blind group. The role of haptic and visual experience thus appears to depend on the task aspect tested.

1 Introduction

The visual and haptic input channels provide us with crucial information concerning the identity and location of objects in peripersonal space. Whereas the sighted depend particularly on vision to represent peripersonal space, the blind are bound to use the haptic system. As a consequence, one may expect that the blind are better, faster, and more efficient in haptically identifying and handling objects in peripersonal space than the sighted, as well as in learning and remembering their locations. Strikingly, however, most studies seem to suggest that visual experience facilitates haptic processing of peripersonal space. Importantly, various different processing components can be distinguished here: eg object handling, object identification, spatiomotor actions, and building a cognitive representation of the spatial locations of objects within reach. It needs to be further examined for which components visual experience might be beneficial and for which greater exclusive reliance on haptic processing, such as takes place in the blind, might be advantageous.

1.1 *Object processing*

With respect to haptic identification accuracy of familiar 3-D objects or depictions of these, either no differences between early-blind and visually experienced (ie late-blind and blindfolded-sighted) groups are reported (Heller 1989b, experiment 1; Morrongiello et al 1994), or differences that favour only the visually experienced, ie the late-blind (Heller 1989b, experiment 2), or both the late-blind and the blindfolded-sighted (Shimizu et al 1993). Several explanations have been put forward to account for such differences. Differences between the late-blind and the blindfolded-sighted could possibly arise from limited exclusive haptic experience in the sighted. We normally look at what our hands are doing, and attentional resources could become dominated by the visual channel in these circumstances. In turn, beneficial effects of visual experience on haptic identification of particularly (familiar) 3-D stimuli (Shimizu et al 1993) may result from similar (Newell et al 2001; James et al 2002) or common representations of haptic and visual form (Reales and Ballesteros 1999) or from a unidirectional enhancement, ie visual experience enhances haptic processing (cf Sathian et al 1997; Amedi et al 2001; Pascual-Leone and Hamilton 2001). In addition, for the inferior performance of the early-blind in 2-D identification tasks (Heller 1989b, experiment 2; Shimizu et al 1993), several theoretical explanations have been put forward, such as problems with making decisions (Heller 1989b), and/or dependence on egocentric coding (Millar 1981; Gaunet et al 1997).

Although no advantage of haptic experience alone for haptic identification accuracy has been reported, there is an indication that it may speed up the identification process, at least in some circumstances: Heller (1989b, experiment 1) found that congenitally blind and late-blind participants were much faster than the blindfolded-sighted on the matching of simple Braille-sized 2-D shapes, while no differences in matching accuracy could be reported. The precise origin of this specific advantage of haptic experience is unclear. It may be due to the size of the objects, where Braille reading experience may facilitate the recognition of patterns on the fingertip. In support of this, Morrongiello et al (1994) did not find identification speed differences between blindfolded-sighted and early-blind children (aged 3 – 8 years) for familiar 3-D stimuli. Another possibility is that the influences of haptic and visual experience depend on the nature of the stimuli: in contrast to the aforementioned studies (Heller 1989b, experiment 2; Shimizu et al 1993; Morrongiello et al 1994) Heller (1989b, experiment 1) used simple and abstract (yet for the greater part familiar) shapes. It may be that visual imagery facilitates the accuracy of the haptic identification of more complex stimuli (Heller 1989a; but see Morrongiello et al 1994), whereas haptic experience increases the speed of the identification process of simple, more abstract shapes. In line with this, Vecchi (1998) suggested that blind individuals do not perform as well on more-demanding spatial tasks and when active elaboration is required.

1.2 *Space processing*

Another dimension of haptic processing concerns the ability to map the spatial location of where things are, as indicated either by efficient spatiomotor actions (eg reaching, grasping) or by generating and manipulating a conscious mental representation of the relevant object locations within reach. Importantly, Millar (1979, 1981, 1988, 1994) proposed that three types of spatial coding are used in peripersonal space—egocentric, allocentric, and movement coding—and showed that visual experience affects the extent to which these three types of coding are adopted. Elsewhere, it has been argued that egocentric coding is employed in fast implicit tasks and used for immediate goal-directed movements, while allocentric coding is used in explicit tasks underlying conscious perception and spatial memory (Milner and Goodale 1995). In the haptic domain, delaying responses or using verbal labels for haptic inputs may stimulate the employment of allocentric reference frames (Zuidhoek et al 2003, 2005). Interestingly, delayed pointing by blindfolded-sighted has indeed been suggested to reveal an allocentric coding pattern, in contrast to early-blind who might be more egocentrically oriented (Rossetti et al 1996; Gaunet and Rossetti 2006). Ungar et al (1995) and Hollins and Kelley (1988) offered unlimited time to participants to learn the objects and their locations. They demonstrated an advantage for the visually experienced in the localisation of objects, yet only after object configuration rotation. This advantage was found to result from qualitative differences in spatial coding of haptic spatial information, with the visually impaired, and the early-blind in particular, relying predominantly on egocentric and movement memory to code spatial locations instead of external frames of reference (see also Gaunet et al 1997).

In short, haptic processing of peripersonal space comprises multiple different components, such as handling objects, performing spatially directed actions upon these objects and their spatial locations, identifying the nature of objects, and constructing a conscious image of where things are within one's reach. The purpose of the present study was to systematically investigate how touch is used to explore peripersonal space for these different components. Central here was the comparison between early-blind (lacking visual experience), late-blind, and blindfolded-sighted individuals (possibly suffering from less reliance on strictly haptic inputs). The main task involved the processing of an object array used in the portable Tactual Performance Test (pTPT), which is part of the Halstead – Reitan Test Battery (Reitan and Wolfson 1993).

Early-blind, late-blind, and blindfolded-sighted individuals learned ten objects (familiar shapes) and their locations during a speeded matching task, which was repeated twice (trials 1 – 3). During these three trials participants were to fit the shapes into matching cut-outs in a board as far as possible, providing information on object handling(1) and spatial learning. In another trial (trial 5), performance was measured after rotation of the object configuration. While the first three trials may primarily depend on manual dexterity, the rotated configuration requires an updating of positions and performance is detached from the stored movement memories. Previous studies (Hollins and Kelley 1988; Ungar et al 1995) have shown an advantage for visually experienced individuals under these circumstances.

Two further trials were carried out to assess the spatial and object memory traces formed after the repeated, speeded testing described above in a different way. One trial required non-speeded relocation of the objects in free space (trial 4). Participants had to place the shapes on a (non-rotated) board of equal size without cut-outs, as accurately as possible. Free-space relocation may entail both exact or coordinate and relative or categorical spatial-position codes. As these two codes are difficult to separate in this situation we only looked at the coordinate distance measures. The last trial (trial 6) required participants to give a verbal description of both the shapes and their locations. The accuracy of verbal descriptions of the shapes may provide insight into the degree to which these were consciously recalled. The verbal location descriptions offer mainly categorical position information.

2 Method

2.1 *Participants*

Table 1 shows the list of participants. Thirteen early-blind, seventeen late-blind, and sixteen sighted people participated in the experiment. The blind were recruited with announcements in magazines for the visually impaired. The sighted participants had blind partners or relatives, or worked (paid or on voluntary basis) in institutions for the blind. None of the participants had neurological or motor deficits. The early-blind group consisted of congenitally blind and early-blind individuals who had become blind before the age of three. Those who were not blind from birth reported no memory of vision whatsoever. All participants in the late-blind group had rich vivid visual memories, and reported having used vision as a primary spatial modality. The blindness of the participants had different etiologies (see table 1). Some late-blind participants were born visually impaired and had gradually become blind during life. Others had lost their sight as a result of accidents. None of the blind participants claimed to have intact peripheral vision. A minority of the blind participants had diffuse light sensations, but denied being able to use this in any form of spatial behaviour (for example, orienting oneself to a specific light source).

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(1) As pointed out by an anonymous referee, object handling would have been better investigated by directly recording the exploratory hand movements (cf Lederman and Klatzky 1987). Now we just have the aggregate performance, ie the time to match all the shapes to their slots in the spatial configuration. Conclusions on differences in manual dexterity underlying matching speed are therefore only indirect, though intuitively seem to make sense.

Table 1. Sample description of the early-blind, the late-blind, and the sighted participants. Means and SDs have been omitted from this table.

Subject number	Occupation	Education level	Sex	Age /y	Etiology and further characteristics	Age of onset/y
Early blind						
1	sports masseuse	secondary school	F	41	Leber's amarosis, ambidexter	0
2	policy worker	university	M	41	retinoblastoma	0
3	computer programmer	higher education	M	33	congenital glaucoma	0
4	office assistant	vocational education	F	49	rubella (mother)	0
5	retired operator	secondary school	M	58	glaucoma, ambidexter	2
6	office assistant	secondary school	F	34	retrolental fibroplasias	0
7	operator	secondary school	M	38	rubella (mother)	2–3
8	translator	higher education	F	30	retrolental fibroplasias	0
9	retired	vocational education	M	64	retinoblastoma	2–3
10	teacher	higher education	M	46	Leber's amarosis	0
11	systems designer	higher education	M	46	retinoblastoma	0–1
12	consultant	secondary school	F	55	retinoblastoma	0–1
13	sound technician	higher education	M	49	retrolental fibroplasias	0
Late blind						
1	physiotherapist	higher education	M	52	accident	10
2	IT employee	higher education	M	57	born partially blind in one eye, glaucoma in other eye	25
3	social worker	vocational education	M	57	Usher's syndrome and an accident	25
4	piano tuner	vocational education	M	40	accident, left-handed	19
5	volunteer	higher education	M	54	macular degeneration (wet form/bleeding)	10
6	office assistant	secondary education	M	64	congenital glaucoma	7
7	operator	secondary school	F	59	not available	9
8	music teacher	higher education	M	64	retinitis pigmentosa	40
9	correspondence clerk	vocational education	M	60	congenital glaucoma	49
10	civil servant	higher education	M	38	brain tumour	4
11	employment-finding for the blind	higher education	M	59	Leber opticus artrosa and glaucoma	32
12	social worker	vocational education	M	53	aniridi and glaucoma	20
13	operator	vocational education	F	58	retinitis pigmentosa	14
14	therapist	secondary school	F	52	born blind in one eye, glaucoma and inflammation of the cornea of the other eye	30
15	school teacher	higher education	F	53	congenital glaucoma	22
16	psychologist	university	F	51	congenital glaucoma	40
17	social worker	higher education	F	39	unknown	35
Sighted controls						
1	editor	higher education	F	32		
2	editor	university	F	30		
3	retired	university	M	58		
4	research	university	M	37		
5	retired	vocational education	F	58		
6	ergotherapist	higher education	F	36		
7	ergotherapist	higher education	F	46		
8	journalist	higher education	M	56		
9	musician	higher education	M	53		

Table 1 (continued)

Subject number	Occupation	Education level	Sex	Age /y	Etiology and further characteristics	Age of onset/y
Sighted controls (continued)						
10	volunteer	vocational education	F	60		
11	personnel coordinator	higher education	F	54		
12	administration	higher education	M	67		
13	housewife	secondary school	F	63		
14	ortho-pedagogue	university	F	40		
15	service manager	higher education	M	48		
16	editor	university	M	51		

Early-blind (EB), late-blind (LB), and blindfolded-sighted (BS) participants were matched for sex ($\chi_2^2 = 1.1$, $p = 0.57$), and verbal IQ, which was assessed with two subscales (vocabulary and similarities) of the Dutch WAIS-III (Wechsler 1997) ($F_{2,43} = 1.4$, $p = 0.3$). Furthermore, the groups were roughly comparable in age ($F_{2,43} = 2.8$, $p = 0.071$) and education ($F_{2,43} = 3.2$, $p = 0.05$) which was coded on a 5-point scale. The education level of particularly the early-blind was slightly lower, but most importantly the WAIS scores indicated comparable intelligence. Most of the participants were employed. Participants were right-handed as assessed with Annett's (1970) handedness questionnaire, except where indicated in table 1 (etiology and further characteristics).

All participants gave their informed consent to inclusion in this study and received payment for their participation. They were naive to all aspects of the tasks, ie they had never seen or felt the setup, were unaware of the experimental purposes, and were never given any feedback.

2.2 *General procedure*

All participants were enrolled in a larger series of studies on spatial cognition in the blind comprising several more tasks reported elsewhere. The latter included haptic parallel setting of two bars, spatial test comprehension (Noordzij et al 2006), a mental imagery test battery (Noordzij et al 2007), and the WAIS. All tasks were conducted during a single session which lasted about a day. As the order of tasks was counterbalanced over participants, half of them performed the present tasks in the morning in the first part of the testing session, whereas the other half performed them during the second part of the testing session in the afternoon. Experimental tasks did not take longer than 30 min to minimise fatigue. In addition to a lunch break (1 h) between the morning and afternoon session and two coffee breaks (10 min), participants were allowed breaks whenever they needed them.

2.3 *Apparatus and stimuli*

The portable tactual-performance test was originally designed as a measure for haptic shape recognition and incidental memory for haptic spatial relations. To serve the present purposes, the test was modified. Figure 1 gives a schematic drawing of the stimulus setup. The stimulus consisted of a 45.5 cm × 30.2 cm × 2.1 cm wooden board containing the ten shape cut-outs and ten different geometrical shapes: a square, oval, star, diamond, hexagon, rectangle, circle, semicircle, triangle, and cross. All shapes were 2.1 cm thick, but varied in their proportions. The smallest shape was 7.5 cm × 7.5 cm (square), the largest 16.7 cm × 7 cm (rectangle). Each shape could fit only in a single cut-out. The board was placed on a table right in front of the seated subject, with the longer sides parallel to the edge of the table. In trial 4, this board was replaced by a board of equal size without cut-outs. A piece of paper showing the outlines of the

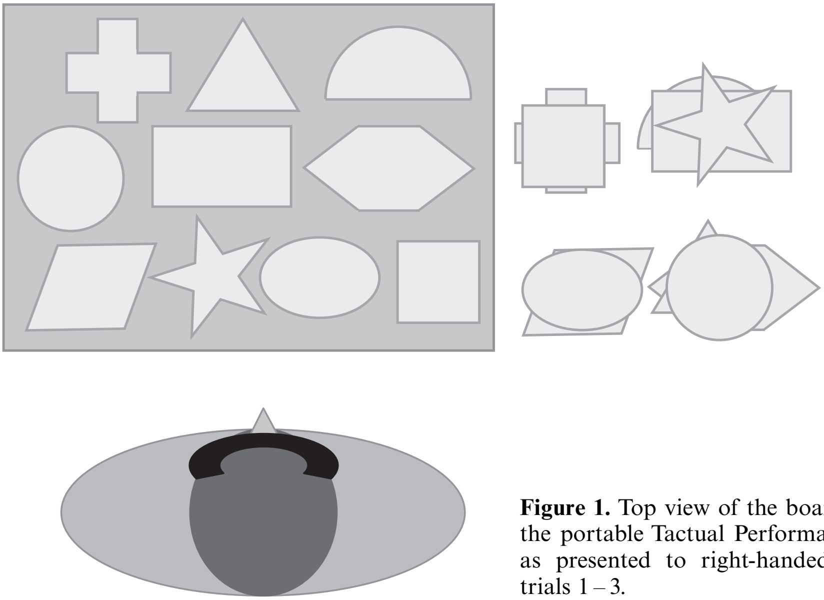

Figure 1. Top view of the board and objects of the portable Tactual Performance Test (pTPT), as presented to right-handed participants in trials 1 – 3.

shapes in their proper locations was attached to this board. During testing, the boards were taped to the table to avoid shifting. The ten shapes were placed in four random piles—two piles of three shapes, and two of two shapes—placed either to the right or to the left of the board, depending on hand preference.

2.4 *Procedure*

Sighted participants and those with residual diffuse-light sensations were blindfolded before the experimenter brought out the board and shapes. The participants were not allowed to explore the board or the shapes before actual testing, and it was not before the start of a trial that they were informed on what was required in that particular trial. In the first three trials, they were asked to fit the shapes into the proper cut-outs as fast as possible. They were allowed to use both hands and were free in choice of strategy. The experimenter started the stopwatch when participants first touched the board or one of the shapes; the stopwatch was stopped right after the participant had correctly placed the last piece. Before trial 4, the board was replaced by a wooden board of equal size and position, but without the cut-outs. Now, participants were to place the shapes on their proper locations as accurately as possible (trial 4). They were allowed to take as much time as they needed; time was not recorded. After participants had completed this task, the locations of the shapes were recorded by outlining them with a pencil on the piece of paper covering the board which also showed the correct outlines. In trial 5, this board was replaced by the original board, but now it was rotated 90° counterclockwise. Participants were verbally notified of this and had to hold the short ends of the board while the experimenter was rotating it in order to clarify what they had been notified of. Next they were asked to again fit the shapes into the proper cut-outs as fast as possible. Once more, time was recorded. After this, both the board and shapes were removed. Now participants were asked to name or describe the objects and describe how the different shapes were situated on the (non-rotated) board, as accurately as possible, and in such a way that a person conversing with the subject could place the shapes in their correct location using their descriptions only (trial 6). Their descriptions were recorded with sound recording equipment.

Although other sequences of trials 4 through 6 are conceivable, we chose to have the non-speeded trial testing relocation of the objects in free space (trial 4) before the rotation trial (trial 5), as we anticipated that rotation of the board might disrupt the exact, coordinate position relocation. Because the verbal response was expected to trigger explicit spatial reasoning, we chose it to be the final trial, in which case it would not affect performance on the other trials.

2.5 *Data analyses*

2.5.1 *General.* As we were interested in the effects of both visual and haptic experience as well as possible interaction effects, we used (general linear model) ANOVAs with the three groups as a between-subjects factor. A posteriori tests are only reported to be significant after correction for multiple comparison (Bonferroni correction). Where necessary, the degrees of freedom were corrected by using Greenhouse – Geisser ε-correction.

2.5.2 *Haptic matching and object configuration learning: trials 1, 2, and 3.* The time (in s) to complete trials 1 through 3 provides information about the haptic matching capacity and implicit learning of an object configuration.

2.5.3 *Rotation: trials 3 and 5.* To examine the effects of rotating the board on speeded haptic matching performance, the differences between the groups in completion time for trial 3 and trial 5 were analysed.

2.5.4 *Coordinate accuracy of free placement of shapes: trial 4.* Coordinate (exact) accuracy of free placement of the shapes was measured to gain insight into object location memory performance after the three previous trials. Our measure of metric accuracy indicated how far an object was placed from its original position (the distance between the geometrical centres of the objects, in cm). This representation might either be more allocentric (ie in terms of an absolute external reference frame) or more egocentric (ie position is laid down with respect to one's own body).

2.5.5 *Verbal descriptions of objects and their spatial locations (free recall): trial 6.* A number of measures was examined. First, we investigated whether visual or haptic experience (or both) affected the number of objects remembered and the way the objects were named and described. To examine possible differences between the descriptions of the objects, we compared the number of objects correctly named (eg calling the cross a "cross" or a "plus sign"), correctly described (eg calling the semicircle a "shape, round at one side and flat at the other"), and with ambiguous, unclear, or incorrect descriptions ("a thing with multiple protruding parts"). The absolute numbers of objects correctly named, objects correctly described, and objects incorrectly described, were used to examine possible differences between the groups with respect to explicit haptic identification.

Second, we investigated whether spatial language differed for the three experimental groups, which may reflect spatial coding strategy differences between the blind and the sighted (cf Brambring 1982). Following Ungar et al (1995), who observed different strategies employed to encode spatial configuration of objects, we examined the number of spatial descriptions in which the object's position (a) was pointed out by referring to the board ("the cross was the top left of the board"); (b) was described with respect to another object ("the triangle was right of the cross); and (c) was described with respect to a part of the participant's body ("the circle was over here", or "the circle was to my left"). In order to get a measure of the characteristics of the descriptions irrespective of possible differences in object descriptions, incorrect or unclear descriptions were also included. Furthermore, we recorded the number of deviant ways to describe the positions of the objects (using the clock face and wind quarters), the number of times visual language was used (calling the semicircle "a setting sun"), and the number of times extra (correct) information was given about the shape of the board, number of rows and columns, or the placement (orientation) of the objects on the board ("the long side of the semicircle was parallel to the long end of the board").

Third, the number of objects verbally placed in their correct categorical position (with any of the above-mentioned referral types) was counted, providing a measure for differences with respect to the correctness of the representation of the relations between the different objects within the configuration.

2.6 *Results*

2.6.1 *Haptic matching speed and object configuration learning: trials 1, 2, and 3.* Figure 2 shows the average performance of the three experimental groups over the four time trials. A 3 (trial) × 3 (group) mixed repeated-measures ANOVA was conducted to examine the learning over the first three trials, as expressed in completion times. Main effects for group ($F_{2,43} = 14.8$, $p < 0.001$) and trial ($F_{2,86} = 31.4$, $p < 0.001$) were found. The main effect of group was expressed in different mean completion times for the groups: EB took 79 s on average to perform the task, LB 75 s, and BS 138 s, indicating (as does figure 2) that the blind were faster than the blindfolded-sighted (EB < BS: $t_{27} = 3.8$, $p = 0.001$ and LB < BS: $t_{31} = 5.9$, $p < 0.001$). The main effect of trial was expressed in different means for trials 1, 2, and 3 which were 125 s, 90 s, and 76 s, respectively. Further analyses showed that this main trial effect expressed significant learning from trial 1 to trial 2 ($t_{45} = 5.1$, $p < 0.001$), and from trial 2 to trial 3 ($t_{45} = 2.7$, $p = 0.01$). A trend towards a group × trial interaction ($F_{4,86} = 2.2$, $p = 0.07$) was obtained, signaling in particular a strong improvement from trial 1 to 2 in the blindfolded-sighted group.

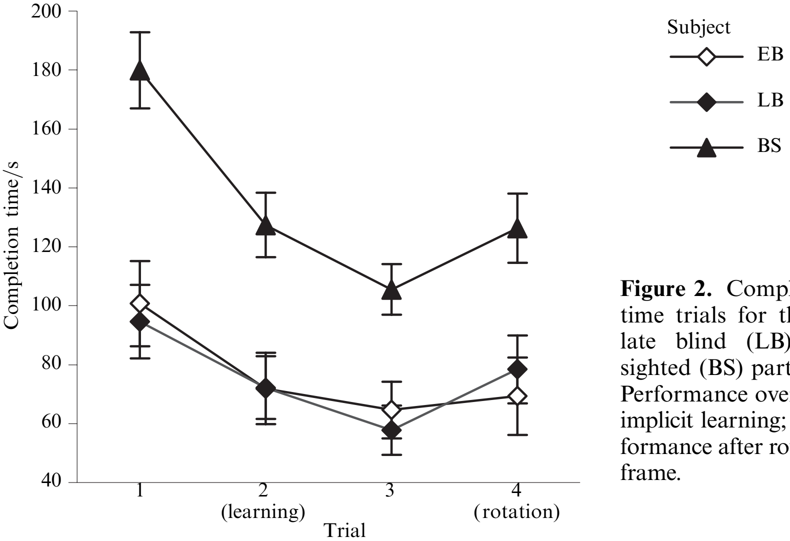

Figure 2. Completion times on the time trials for the early blind (EB), late blind (LB), and blindfolded-sighted (BS) participants, in seconds. Performance over trials 1 to 3 reflects implicit learning; trial 5 expresses performance after rotation of the stimulus frame.

2.6.2 *Effects of rotation on completion time: trials 3 and 5.* A 2 (trials: trial 3 vs 5) × 3 (group) mixed ANOVA showed main effects of trial ($F_{1,43} = 8.0$, $p = 0.007$) and group ($F_{2,43} = 8.8$, $p = 0.001$), yet no group by trial interaction ($F_{2,43} = 0.9$). The main effect of trial was a decline in performance from trial 3 to trial 5: mean completion times went up from 76 s to 91 s. The main effect of group indicated a difference in mean completion times between the groups over both trials: 67 s, 68 s, and 116 s, for EB, LB, and BS, respectively, showing that the blind outperform the blindfolded-sighted on trials 3 and 5 (EB < BS: $t_{27} = 3.5$, $p = 0.002$; and LB < BS: $t_{31} = 3.8$, $p = 0.001$).

2.6.3 *Accuracy of coordinate coding: trial 4.* The metric distance scores were 9.9 (1.6) for the EB, 8.3 (1.0) for the LB, and 10.2 (0.9) for the BS. An ANOVA comparing the scores of the three groups showed no difference between the groups for metric ('coordinate') distance ($F_{2,43} = 0.850$, $p = 0.44$).

2.6.4 *Verbal descriptions of objects and their spatial locations (free recall): trial 6.*
Object descriptions. Table 2 shows group means. We found no differences between the three groups with respect to the total number of objects described ($F_{2,43} = 1.4$). In addition, no differences between the groups were found for the number of correctly named objects, correctly described objects, and incorrectly described objects. This suggests that there were no differences between the groups with respect to recalling and identifying the objects by touch, and naming and describing them.

Table 2. Mean numbers (SE) of objects recalled and the quality of the object descriptions given by the experimental groups.

Group	Total	Correctly named	Correctly described	Incorrectly described
EB	8.3 (0.5)	6.5 (0.5)	0.5 (0.3)	1.2 (0.3)
LB	9.1 (0.2)	7.2 (0.5)	0.5 (0.2)	1.4 (0.2)
BS	8.8 (0.3)	7.2 (0.4)	0.3 (0.1)	1.3 (0.3)
Average	8.7 (0.2)	7.0 (0.3)	0.4 (0.1)	1.3 (0.1)

Spatial descriptions. An ANOVA was conducted with type of reference in description (ie with respect to other objects vs with respect to board) as a within-subjects factor and group as a between-subjects factor (see table 3). No main group effect was found ($F_{2,43} = 1.46$, $p = 0.24$), nor a type of reference preference ($F_{1,43} = 2.18$, $p = 0.15$). The interaction of group by type of reference was marginally significant ($F_{2,43} = 3.19$, $p = 0.05$), suggesting that the blind groups appeared to use more object-oriented descriptions than the blindfolded-sighted ($F_{2,43} = 3.4$, $p = 0.043$), while the latter had more descriptions referring to the board (though this was not significant in a test of the group effect for only the descriptions referring to the board, $F_{2,43} = 1.9$, $p = 0.16$). No differences or trends could be reported for the number of descriptions with respect to (parts of the) participant's body, or other reference classes (wind quarters, clock face), which were used only incidentally (means: 0.35, 0.09, and 0.09, respectively). In line with this, no differences were found with respect to (the low) frequency of 'visual' language or verbal expressions conveying additional spatial information (means: 0.35 and 0.46, respectively).

Table 3. Mean numbers (SE) of total amount of spatial descriptions, referrals to other objects, to the board and to other, and the number of objects correctly verbally positioned.

Group	Total	Object descriptions	Board descriptions	Other	Correctly positioned
EB	9.0 (0.8)	4.1 (0.8)	4.2 (0.5)	0.7 (0.5)	4.9 (0.9)
LB	10.2 (0.4)	5.1 (0.6)	4.6 (0.6)	0.5 (0.2)	6.3 (0.6)
BS	9.0 (0.8)	2.6 (0.7)	5.8 (0.7)	0.6 (0.3)	3.8 (0.7)
Average	9.4 (0.4)	4.0 (0.4)	5.0 (0.4)	0.6 (0.2)	5.0 (0.4)

Verbal positioning. An ANOVA pointed out that the number of objects verbally placed in the correct categorical position was different for the three groups ($F_{2,43} = 3.7$, $p = 0.034$). Further analyses showed that this was caused by a difference between the LB and the BS ($t_{31} = 2.8$, $p = 0.002$). The other contrasts were not significant. As table 3 makes clear, it seems that particularly combining exclusive haptic processing with past visual experience gives an advantage when verbally describing the locations of the objects in the current task, over either having just haptic experience or having a strong preference for the visual modality.

3 General discussion

The goal of the present study was a systematic investigation of how early-blind and late-blind individuals compare to blindfolded-sighted individuals on different aspects of haptic processing of peripersonal space. Specifically, we examined both object- and space-processing components, using a test in which objects had to be fitted into corresponding slots in a spatial array frame. Later, free recall of object locations was measured as well as verbal descriptions of which objects were present and where they were located.

The completion times of the groups for the first three trials suggested that primarily haptic experience is important for the speeded handling and motor matching of simple familiar 3-D shapes to the corresponding cut-outs. The blind were much faster than the blindfolded-sighted. This is in accordance with findings by Heller on the speeded haptic matching of comparable, yet smaller, 2-D shapes (1989b). Interestingly, all three groups showed considerable improvement over the three trials. Although the blind displayed faster object-to-location matching, they did not display faster learning than the blindfolded-sighted. In fact, there was a nonsignificant trend for the blindfolded-sighted to improve even more than the blind, particularly from the first to the second trial. While the constriction to exclusive haptic inputs on peripersonal space may have given the blind an advantage in handling objects and performing spatiomotor actions upon them, such as fitting them in the corresponding slots, blindfolded-sighted individuals partly catch up when more practice with exclusive haptic processing is forced upon them (eg trials 1 – 3 and 5). This finding resembles those reported in other studies where blindfolded-sighted participants appeared to show greater learning rates than blind individuals (cf Craig 1988; Grant et al 2000). Notice that it might be worthwhile to see whether the general pattern also holds up for less-familiar, more-complex shapes.

In trial 5 the board was rotated, after which subjects had again to match the objects to the proper slots as fast as possible. Not surprisingly, rotating the board caused an increase in completion time. However, this increase was the same for the congenitally blind, late-blind, and blindfolded-sighted groups. Rotating the display limits the use of previously stored movement memories and requires positional updating. Elsewhere the blind were found to suffer more from positional-updating circumstances (Hollins and Kelley 1988; Ungar et al 1995). However, these studies asked for an explicit relocation of objects, and updating was enforced by a whole-body movement of the observer relative to a fixed display, rather than by a rotation of the board relative to a fixed observer as in the current study. Importantly, Montello et al (1999) showed that body rotation leads to a specific egocentric recalibration, using a short-term memory trace of the original forward-facing direction. Earlier work by Marmor and Zaback (1976) indicated that blind individuals were closer than blindfolded-sighted persons in mentally rotating pairs of tactile forms until they matched. The linear function of angular discrepancy between the forms was present, though, in both groups. Hollins (1986) found similar haptic mental-rotation functions for the blind and sighted, and when taking into account the greater variability in the use of reference frame in the latter, initial differences in mental-rotation rates virtually disappeared. The foregoing thus suggests that the roles of visual and haptic experience with respect to mental-rotation tasks depend on the specific nature of the task. The effect of visual experience on performance when processing of peripersonal space is tested with the array rotated rather than the observer should be examined in future research (cf Pasqualotto and Newell, submitted).

Interestingly, the non-speeded free placement of the objects on the board without the cutouts in trial 4 did not reveal differences in coordinate (exact) positional-memory scores between the groups. A similar observation was made in the last trial (trial 6). The three groups performed similarly with respect to naming and describing the objects in the display. This is in line with reports on haptic identification of 3-D familiar objects (Shimizu et al 1993; Morrongiello et al 1994). One speculative explanation of this difference could be that the apparent superior haptic dexterity in the blind individuals in the speeded matching conditions follows from a more refined implicit level of processing while free space recall and verbal labeling of the displayed objects requires employment of a more explicit, conscious representation. That is, efficient handling of shapes and fitting them in the proper slots can occur even without any conscious awareness of what these shapes are and where their places were. In contrast, placing the shapes in free space requires conscious retrieval and usage of a spatial map. This seems even more the case when giving a verbal description. Group differences thus might be modulated by the nature of the task on the implicit/explicit dimension. However, in the present setup trials cannot exclusively be labeled as either implicit or explicit. Free spatial recall in trial 4 might also benefit from an implicit sense of where things were. Similarly, speeded matching in trials 2 and 3 might profit from a gradually developing conscious map, and, in any case, there was no sign of improved implicit learning by the blind in these trials.

Importantly, verbal description of spatial locations did reveal a beneficial role of visual experience. We found that the explicit spatial knowledge of the object configuration benefits from visual experience, yet only when combined with sufficient haptic experience: the spatial verbal description (trial 6) resulted in an advantage, particularly for the late-blind. This indicates that, in the present task, abundant (exclusive) haptic experience was a prerequisite for visual experience to support explicit categorical coding of the location of haptically explored objects.

With respect to spatial-coding strategies, the descriptions of the spatial location of the objects revealed an interesting difference between the blind and the blindfolded-sighted groups. While the sighted used more board referrals than the blind to point out the locations of objects (allocentric, extrinsic; cf Ungar et al 1995), the blind referred more to other objects on the board (allocentric, intrinsic) than the sighted. Although both types of descriptions can be called allocentric, one could argue that the nature of the descriptions is different, and may be indicative of differences in which the spatial information is coded in the blind and the blindfolded-sighted. We wish to speculate that referring to the surrounding frame (ie the board) is the expression of a map-like, bird-view representation, and that referring to other objects to point out an object's location reflects a spatial representation in terms of a route (cf Brambring 1982). In line with this, Noordzij et al (2006) have shown that, when generating a spatial representation of a large scale environment from verbal descriptions, the blind perform better on distance-comparison tasks after listening to a route description than a bird-view description.

The pattern described above clearly indicates that the comparison between blind and blindfolded-sighted individuals leads to different outcomes for the various aspects of haptic processing of peripersonal space under scrutiny. Similarly, Gaunet and Rossetti (2006) describe a diverse pattern of differences for the different parameters in a (delayed) pointing task: direction and amplitude errors and absolute distance errors did reveal differences between the blind groups on the one hand and the blindfolded-sighted group on the other. Ellipse surface and ellipse elongation did not, however. Systematic investigation of the task at hand is therefore necessary. The present results clearly confirm this notion by showing a qualitative pattern of group differences for the various aspects of haptic processing of object space.

In sum, the present results indicate that the need to rely more exclusively on haptic inputs stimulates haptic dexterity in the blind, leading, in particular, to more efficient handling of objects and placing them in the proper spatial locations than by blindfolded-sighted individuals. Importantly, visual experience may be beneficial when one has to place objects in free space and verbally describe the object and spatial configuration. Clearly, both haptic and visual experience affect processing of peripersonal space, but they do so for different aspects.

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References

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

Annett M, 1970 "A classification of hand preference by association analysis" *British Journal of Psychology* **61** 303 – 321

Brambring M, 1982 "Language and geographical orientation for the blind", in *Speech, Place and Action* Eds R J Jarvella, W Klein (New York: John Wiley and Sons) pp 203 – 218

Craig J C, 1988 "The role of experience in tactual pattern perception: A preliminary report" *International Journal of Rehabilitation Research* **11** 167 – 171

Gaunet F, Martinez J-L, Thinus-Blanc C, 1997 "Early-blind subjects' spatial representation of manipulatory space: exploratory strategies and reaction to change" *Perception* **26** 345 – 366

Gaunet F, Rossetti Y, 2006 "Effects of visual deprivation on space representation: Immediate and delayed pointing toward memorised proprioceptive targets" *Perception* **35** 107 – 124

Grant A C, Thiagarajah M C, Sathian K, 2000 "Tactile perception in blind Braille readers: A psychophysical study of acuity and hyperacuity using gratings and dot patterns" *Perception & Psychophysics* **62** 301 – 312

Heller M A, 1989a "Tactile memory in sighted and blind observers: the influence of orientation and rate of presentation" *Perception* **18** 121 – 133

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

Hollins M, 1986 "Haptic mental rotation: More consistent in blind subjects?" *Journal of Visual Impairment and Blindness* **80** 950 – 952

Hollins M, Kelley E K, 1988 "Spatial updating in blind and sighted people" *Perception & Psychophysics* **43** 380 – 388

James T W, Humphrey G K, Gati J S, Servos P, Menon K S, Goodale M A, 2002 "Haptic study of three-dimensional objects activates extrastriate visual areas" *Neuropsychologica* **40** 1706 – 1714

Lederman S J, Klatzky R L, 1987 "Hand movements: a window into haptic object recognition" *Cognitive Psychology* **19** 342 – 368

Marmor G S, Zaback L A, 1976 "Mental rotation by the blind: does mental rotation depend on visual imagery?" *Journal of Experimental Psychology: Human Perception and Performance* **2** 515 – 521

Millar S, 1979 "The utilization of external and movement cues in simple spatial tasks by blind and sighted children" *Perception* **8** 11 – 20

Millar S, 1981 "Self reference and movement cues in coding location by blind and sighted children" *Perception* **10** 255 – 264

Millar S, 1988 "Models of sensory deprivation: The nature/nurture dichotomy and spatial representation in the blind" *International Journal of Behavioral Development* **11** 69 – 87

Millar S, 1994 *Understanding and Representing Space: Theory and Evidence from Studies with Blind and Sighted Children* (Oxford: Clarendon Press/Oxford University Press)

Milner A D, Goodale M A, 1995 *The Visual Brain in Action* (Oxford: Oxford University Press)

Montello D R, Richardson A E, Hegarty M, Provenza M, 1999 "A comparison of methods for estimating directions in egocentric space" *Perception* **28** 981 – 1000

Morrongiello B A, Humphrey K, Timney B, Choi J, Rocca P T, 1994 "Tactual object exploration and recognition in blind and sighted children" *Perception* **23** 833 – 848

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

Noordzij M L, Zuidhoek S, Postma A, 2006 "The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions" *Cognition* **100** 321 – 342

Noordzij M L, Zuidhoek S, Postma A, 2007 "The influence of visual experience on visual and spatial imagery" *Perception* **36** 101 – 112

Pascual-Leone A, Hamilton R H, 2001 "The metamodal organization of the brain" *Progress in Brain Research* **134** 427 – 445

Pasqualotto A, Newell F N, submitted "The role of visual experience on the representation and updating of novel haptic scenes"

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

Reitan R M, Wolfson D, 1993 *The Halstead – Reitan Neuropsychological Test Battery: Theory and Clinical Interpretation* (Tucson, AZ: Neuropsychology Press)

Rossetti Y, Gaunet F, Thinus-Blanc C, 1996 "Early visual experience affects memorization and spatial representation of proprioceptive targets" *NeuroReport* **7** 1219 – 1223

Sathian K, Zangaladze A, Hoffman J M, Grafton S T, 1997 "Feeling with the mind's eye" *NeuroReport* **8** 3877 – 3881

Shimizu Y, Saida S, Shimura H, 1993 "Tactile pattern recognition by graphic display: Importance of 3-D information for haptic perception of familiar objects" *Perception & Psychophysics* **53** 43 – 48

Ungar S, Blades M, Spencer C, 1995 "Mental rotation of a tactile layout by young visually impaired children" *Perception* **24** 891 – 900

Vecchi T, 1998 "Visuo-spatial imagery in congenitally totally blind people" *Memory* **6** 91 – 102

Wechsler D, 1997 *Wechsler Adult Intelligence Scale* third edition (San Antonio, TX: The Psychological Corporation)

Zuidhoek S, Kappers A M L, Van der Lubbe R, Postma A, 2003 "Delay improves performance on a haptic spatial matching task" *Experimental Brain Research* **149** 320 – 330

Zuidhoek S, Kappers A M L, Postma A, 2005 "Effects of hand orientation and delay on the verbal judgment of haptically perceived orientation" *Perception* **34** 741 – 755

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