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The role of visual experience on the representation and updating of novel haptic scenes

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Abstract

We investigated the role of visual experience on the spatial representation and updating of haptic scenes by comparing recognition performance across sighted, congenitally and late blind participants. We first established that spatial updating occurs in sighted individuals to haptic scenes of novel objects. All participants were required to recognise a previously learned haptic scene of novel objects presented across the same or different orientation as learning whilst they either remained in the same position to moved to a new position relative to the scene. Scene rotation incurred a cost in recognition performance in all groups. However, overall haptic scene recognition performance was worse in the congenitally blind group. Moreover, unlike the late blind or sighted groups, the congenitally blind group were unable to compensate for the cost in scene rotation with observer motion. Our results suggest that vision plays an important role in representing and updating spatial information encoded through touch and have important implications for the role of vision in the development of neuronal areas involved in spatial cognition.

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1. Introduction

We previously reported that both visual and haptic scenes of objects are stored in memory as egocentric representations (Newell, Woods, Mernagh, & Bülthoff, 2005) and that these representations are similarly updated with observer movement (Pasqualotto, Finucane, & Newell, 2005). Our findings extended a previous literature on spatial updating within the visual domain (e.g. Burgess, Spiers, & Paleologou, 2004; Simons & Wang, 1998; Wang & Simons, 1999; Wraga, Creem-Regehr, & Proffitt, 2004) by providing evidence for updating within the haptic domain. Specifically, we found that when participants moved to a novel viewpoint of a scene previously learned through touch, this movement could compensate for the consequent change in the viewpoint of the scene in comparison to when the scene was rotated by the same amount relative to a passive observer. More recently, we found that observer motion could compensate for a change in scene orientation when recognition was performed across modalities suggesting that spatial updating is multisensory (Newell, Finucane, Pasqualotto, & Vendrell, submitted for publication). Indeed our findings also suggested that visual information may mediate the crossmodal spatial updating process since when observers were blindfolded during movement spatial updating was impaired. Here, we investigated to what extent visual experience is necessary for efficient representation and updating of haptic spatial information by comparing recognition performance across sighted and blind individuals with and without visual experience (i.e. late and congenitally blind individuals, respectively).

As Simons and Wang (1998) and others have previously reported several cues can influence updating namely kinaesthetic, proprioceptive, vestibular and visual (e.g. optic flow) information (e.g. Burgess et al., 2004; Simons & Wang, 1998; Wang & Simons, 1999; Wraga et al., 2004).

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To assess the role of visual information on spatial updating of visual scenes, Simons and Wang effectively removed background visual cues that could mediate updating by darkening the room where the participant performed the task (whilst still allowing the test objects to be viewed). This manipulation, however, did not disrupt the spatial updating process (Simons & Wang, 1998, Experiment 2) suggesting that background visual landmarks present in the test room were not used for spatial updating. However, when visual, vestibular and proprioceptive cues were masked, by wheeling the participant to the new viewpoint of the scene while their eyes were closed, spatial updating was significantly reduced (Experiment 3) suggesting that some combination of cues from across these senses is necessary for updating to occur.

In our studies involving spatial updating of haptic and visual scenes, we found that blindfolding sighted observers during self-motion significantly reduced the benefit of spatial updating on crossmodal scene recognition (Newell et al., submitted for publication) suggesting that optic flow may be an important cue for updating representations of scenes across modalities. Although it is unclear why Simons and Wang found no effect on spatial updating of removing background visual landmark information, which effectively removed cues to optic flow during self-motion, whereas we found a significant cost when all visual information was blocked, it is still possible that vision is necessary for spatial updating in other modalities. For example, it may be the case that vision plays an important role in providing precision for representing spatial information in other modalities (Kennett, Taylor-Clarke, & Haggard, 2001) or for integrating information across modalities (e.g. Röder, Rösler, & Spence, 2004) which consequently allows for more efficient representation and updating of this spatial information. If so, then we might expect that visual deprivation may impair spatial updating in other modalities, due to less than optimal representations of spatial information. On the other hand, early visual experience may be sufficient to allow for the optimal development of the relevant neural substrates involved in spatial cognition, consequently efficient representation and updating of spatial information, even in the absence of visual cues during the task, might be expected (as suggested by the results of Simons & Wang, 1998). If this is the case then individuals with visual experience (both early and throughout a lifetime) will be more efficient at representing spatial information and will perform better at updating representations of haptic scenes than those without any visual experience.

Several studies have provided evidence that the posterior parietal cortex (PPC) and the hippocampus act as the neural substrates underlying spatial cognition in humans (e.g. Crane & Milner, 2005; King, Burgess, Hartley, Vargha-Khadem, & O'Keefe, 2002; Maguire et al., 2003; Merriam, Genovese, & Colby, 2003; Smith & Milner, 1989; Vallar et al., 1999). Most of these studies, however, have concentrated on visuo-spatial processing or visual navigation, with the exception of Zhang et al. (2005) and Kitada et al. (2006) who have shown activation in PPC to tactile tasks. The extent to which modalities other than vision contribute to normal processing and activation in the hippocampus in humans, however, is unknown.

Research from the animal literature suggests that vision plays an important role in cortical processing for spatial navigation. For the rat, visual cues dominate in navigation in familiar environments, however, rats blind early on in life show similar 'place cell' firing activity as sighted rats (Save, Cressant, Thinus-Blanc, & Poucet, 1998), suggesting that sensory substitution can be learned for efficient navigation. This finding is consistent with reports from the human literature that congenitally blind individuals are often unimpaired at navigation tasks (e.g. Hollins & Kelley, 1988). On the other hand, rats rendered cortically blind (by lesioning the visual cortex), display inefficient place cell firing in the hippocampus (Paz-Villagrán, Lenck-Santini, Save, & Poucet, 2002) suggesting that the visual system plays an important role in normal spatial cognition (see also Tees, Midgley, & Nesbit, 1981). Moreover, it is argued that vision may provide the reference frame to which all other sensory information is calibrated (Poucet, Lenck-Santini, Paz-Villagrán, & Save, 2003).

Consistent with the literature on early blindness in animals, congenital blindness in humans may have no effect on spatial perception due to learned sensory substitution suggesting that other sensory information is sufficient for normal processing in brain structures involved in spatial cognition. For example, neuroimaging studies have found that visual cortical areas can be recruited during tactile tasks in congenitally blind but not sighted individuals (Sadato et al., 1996) suggesting that processes normally associated with vision may be adopted or recruited by the tactile system in the absence of visual input. Moreover, this recruitment may depend on the onset of the blindness (Sadato, Okada, Honda, & Yonekura, 2002) suggesting a benefit in performance when vision was deprived earlier rather than later in life. On the other hand, congenital blindness in humans may result in an impairment of spatial representation and updating if spatial cognition depends on visual processing. In this case, the absence of vision may affect efficient processing in brain areas involved in spatial cognition, particularly the parietal cortex and possibly hippocampal areas.

The findings of many behavioural studies suggest that vision is necessary to acquire spatial knowledge (Byrne & Salter, 1983; Gaunet, Martinez, & Thinus-Blanc, 1997; Rieser, Guth, & Hill, 1986; Rieser, Hill, Talor, Bradfield, & Rosen, 1992; see Kitchin, Blades, & Golledge, 1997 for a review). Accordingly, congenital blindness is argued to be associated with a permanent impairment of performance in spatial tasks. On the other hand, it is argued that congenital blindness does not completely impair the acquisition of spatial knowledge, but that in the absence of visual experience the representation of spatial information is less efficient (Hill et al., 1993; Millar, 1994; Passini &

Proulx, 1988; Thinus-Blanc & Gaunet, 1997). For instance, according to Hill et al., congenital blindness is associated with the use of inefficient spatial exploration strategies, although these can be corrected to allow congenitally blind individuals to perform spatial tasks as well as sighted individuals. As such, some studies have reported that congenitally blind individuals exhibit excellent performance in spatial tasks (e.g. Hollins & Kelley, 1988; Loomis et al., 1993). However, in general the literature suggests that without adopting task-related strategies to efficiently encode spatial information, the representation of this information without visual experience is less than optimal. If spatial information is not represented optimally, then we might expect that updating this information is consequently compromised.

Previous studies have investigated the role of spatial updating in blind individuals by comparing their performance to blindfolded sighted individuals (e.g. Hollins & Kelley, 1988; Lehtinen-Railo & Juurmaa, 1994). For example, Hollins and Kelley compared spatial updating of haptic scenes across congenitally blind and blindfolded sighted participants and found better updating performance in the sighted group. However, since late blind participants were not tested it is not possible to disentangle the effects attributed to blindness per se from the lack of visual experience. In other words, blindness may have contributed to the cost in the task irrespective of visual experience. In a later study, Lehtinen-Railo and Juurmaa (see their Experiment 1) found further evidence to suggest that visual experience mediates spatial updating within the tactile domain: they found that late blind and blindfolded sighted individuals performed better than the congenitally blind individuals in a task which required judging the positions of objects relative to an external frame after either real or imaginary movement around the display. Specifically, participants were required to either imagine moving to a new position relative to the display of objects or were guided around the room in a random walk until reaching the new position. Interestingly, the authors found no differences in type of motion across groups, however, it is not clear whether poor performance in the congenitally blind group was due to the difficultly of achieving spatial updating from inherently noisy (i.e. random or imagined) walks or whether spatial updating is indeed generally poor in this population.

Although the evidence seems consistent that spatial updating is relatively poor in the congenitally blind, the underlying aetiology of this difference in performance is not well understood from these previous studies (Hollins & Kelley, 1988; Lehtinen-Railo & Juurmaa, 1994). For example, poor updating performance may be due to either an impairment in the spatial updating process in the early blind or to differences in the underlying representation of spatial information between individuals with and without visual experience. In other words, it remains possible that poor spatial performance is due to *either* impaired updating, inefficient representation of spatial information or both. If performance was related to an inefficient representation of spatial information in congenitally blind persons, then we would expect that scene recognition performance would be impaired in this group relative to the late blind group. That is, even without observer motion, the recognition of haptically encoded scenes would be worse in the congenitally than late blind group. On the other hand, if spatial updating is compromised then we would expect differences in performance between the groups only when they are required to recognise a scene after self-motion to a new scene position. As previous studies suggest, late blind persons may be better at spatially updating the scene during motion than congenitally blind. If both processes are impaired then we would expect a general cost in overall performance coupled with poor spatial updating in the congenitally blind relative to the late blind group. None of the previous studies on spatial updating across blind and sighted individuals specifically tried to elucidate the role of visual experience on these two distinct mechanisms (i.e. representation and updating) in the same population. For example, some studies have found that a lack of early visual experience impairs the construction of an efficient, arguably allocentric, representation of space, i.e. a representation which codes for the position of objects relative to each other (see e.g. Gaunet & Rossetti, 2006; Rossetti, Gaunet, & Thinus-Blanc, 1996) whereas others have reported relatively poor spatial updating performance in congenitally blind (e.g. Hollins & Kelley, 1988; Lehtinen-Railo & Juurmaa, 1994).

In sum, the aim of our present study was to investigate the effect of visual experience on the representation of spatial information in the tactile domain and whether visual experience is necessary for updating these spatial representations with observer motion. To that end, we tested performance across late and congenitally blind participants on a haptic scene recognition task. Prior to this experiment we tested performance on our scene of novel objects with a group of sighted participants in order to ensure that our previous findings on haptic updating with scenes of familiar objects generalised to scenes of novel objects. In both experiments, haptic scenes were presented in either the same position as learning or were rotated and participants either remained in the same position as test or walked directly to the new position. We investigated the nature of spatial representations by assessing whether a similar performance cost with scene rotation occurred in all groups, as previously reported for both visual and haptic familiar scene recognition in sighted individuals (see e.g. Diwadkar & McNamara, 1997; Newell et al., 2005). We then tested whether such a cost was compensated by the observer moving to the same new viewpoint and whether this updating was dependent on visual experience.

2. Experiment 1

Experiment 1 was designed to investigate whether our previous results, that haptic scenes of familiar objects are spatially updated (Pasqualotto et al., 2005), generalise to scenes of novel objects. We wanted to use novel objects to avoid any effects of object familiarity or verbal labels on performance both in the sighted group of participants but also in our visually impaired participants in Experiment 2.

2.1. Method

2.1.1. Participants

Ten staff members of the Conservatoire National des Arts et Métiers, Paris, France volunteered to take part to this experiment and gave written informed consent prior to the experiment. Six participants were female and all had a mean age of 45.6 years. All reported normal or corrected to normal vision and none reported any tactile impairments. The study was approved by the Trinity College, School of Psychology Ethics Committee.

2.1.2. Apparatus

The stimuli used in both experiments reported here consisted of 12 novel objects which were created from white modelling plaster. Each object comprised of a random configuration of four basic shapes glued together: triangle (5 cm base, 2.5 cm height and 1 cm thick), sphere (2 cm diameter), arc (based on a semicircle with the diameter of 5 cm, 1.5 cm wide and 1.5 cm thick) and rectangular parallelepiped (3 cm base, 1 cm height and 1.5 cm thick). The object parts were, in turn, mounted on a base support that was 0.8 cm thick. Six of these supports were square (3.5 by 3.5 cm) and six others were rectangular (3.5 by 6 cm). For half of the stimulus set of objects, the four components were arranged on the pedestal in order to obtain 'tall' objects (at least 4.5 cm in height) and for the other half of the stimulus set parts were arranged into 'short' objects (maximum 4 cm in height). The resulting 12 stimuli consisted of three tall square-based, three tall rectangular-based, three short square-based and three short rectangular-based objects.

See Fig. 1 for an illustration of the apparatus used. Two chairs were positioned equidistant from the platform and 45° apart from each other relative to the centre of the platform. The scene platform was obscured from view by a curtain which surrounded the platform. This curtain was not required in Experiment 2. For each participant the distance from the platform was adjusted in order to allow them to reach comfortably its furthest edge. If the platform was moved then the position of the chairs was readjusted to maintain a constant 45° between positions relative to the platform's centre.

In each trial, seven objects were randomly chosen from the full set and firmly fixed on a rotatable circular platform (33 cm in diameter). These objects were randomly positioned with the constraint that they were placed at a distance of at least 5 cm from each other. The platform was positioned securely onto a supporting table.

2.1.3. Design

The experiment was based on a 2×2 within subjects design with scene position relative to the observer (unchanged or changed by 45°) and observer position (unchanged or changed by 45°) as factors. Trials were blocked into each of the resulting four conditions. That is, in two of the blocked conditions the participant remained in the same position (Pu) but the scene was presented either unchanged (Su) or changed (Sc) with respect to its orientation, yielding the blocked conditions of PuSu and PuSc. In the remaining two blocks, the participant changed position between learning and test and again the scene was either in the same orientation as learning or rotated (PcSu and PcSc). There were a total of 24 trials in the experiment with six trials in each blocked condition. The order of the blocks was counter-balanced across participants.

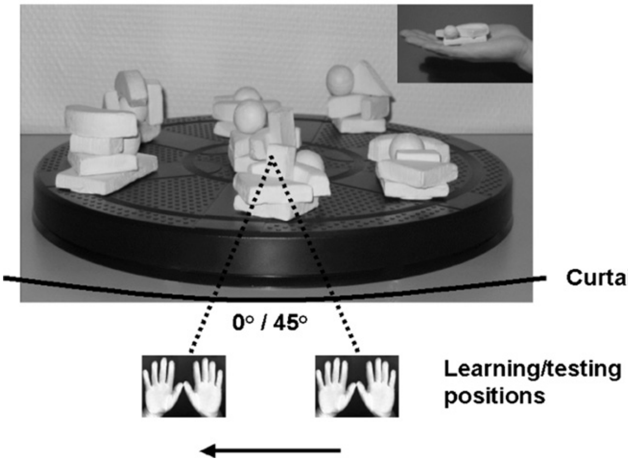

Fig. 1. An illustration of our experimental apparatus and novel stimuli used in our experiment. During the experiment, the circular platform could be rotated 45° in a clockwise direction relative to the participant. Furthermore, in half of all trials, the participant was required to move in a clockwise direction from their original seating position to the new position. This achieved either a 45° change from the learning position in the PcSu condition or the same position was presented during learning and test in the PcSc condition. Note that the position change of the scene was equivalent between the PuSc and PcSu conditions (i.e. 45°), and also between the PuSu and PcSc conditions (i.e. 0°).

2.1.4. Procedure

Prior to the experiment, the amount and direction of the scene rotation used in the experiment was demonstrated to the participants by placing their hands on the platform. Participants performed two practice trials before the actual experiment to familiarize themselves with the task, receive feedback and pose any questions.

There were two phases to each trial, a learning and a test phase, separated by an inter-stimulus interval of 20 s (ISI). In the learning phase participants explored the scene of seven objects for 60 s using both hands. After learning the participants removed their hands from the scene and the experimenter moved one of the seven objects in the scene to a new position. The target object was displaced by 5 cm in any direction, resulting in both a coordinate and categorical change in its position relative to all other objects in the scene (see e.g. Postma & Laeng, 2006), but it maintained its original orientation within the scene. To mask the sound made of the object being moved (i.e. a potential cue for recognising the displaced target), the experimenter removed and returned a number of objects to and from their original position. After the ISI, the participant re-explored the scene and their task was to identify the displaced object. There was no time limit for responding although participants were prompted to respond if 2 minutes had elapsed. Performance was measured in terms of number of correct responses.

After learning and according to the experimental conditions, a scene was either rotated by 45° in a clockwise direction (Sc), or it remained in the same orientation as learning (Su). For half of the Su and Sc trials the participants moved to a new position (Pc) (i.e. moved from one chair to the other placed 45° apart in a clockwise direction) or they remained at the same position (Pu). In the trials where the participant's position was unchanged (Pu), they were requested to stand up, take a few steps and sit down again on the same chair. This movement was required to control for any effects due to the body movement in the condition where the participant's position changed. The experimental conditions were presented in four different blocks and participants were informed of the nature of the experimental condition prior to each block. Participants could take a self-timed break between blocks. The experiment took approximately 60 minutes to complete.

2.2. Results and discussion

The mean percentage of correct responses across all conditions is plotted in Fig. 2. Performance in all conditions was greater than chance (chance level was 1/7 or 14.3%). A two-way ANOVA was performed on the correct responses with participants' position (Pu or Pc) and scene orientation (Su or Sc) as within-subject factors. We found a main effect of scene orientation [$F(1,9) = 27.56$, $p < .01$], with better performance when the scene was not rotated than when it was rotated by 45°. There was no effect of participants' position [$F(1,9) < 1$]. However, we found a significant interaction between participant and scene positions [$F(1,9) = 11.00$, $p < .01$]. A post hoc, Newman–Keuls analysis revealed a significant effect of scene rotation when the participant remained stationary ($p < .05$). In other words, performance in the PuSu condition was significantly better than in the PuSc condition. However, there was no significant difference in performance across scene rotations when the participant changed their position (i.e. PcSu = PcSc). Moreover, performance in the PuSc condition was significantly worse than in either of the conditions where the participant moved, PcSu and PcSc ($p < .05$).

The results of this experiment confirmed our previous findings that haptic scenes are updated with observer motion, but also extended these findings by providing evidence that updating can also occur for scenes of unfamiliar objects. Moreover, since in all the experimental conditions the performance was above chance level, these results suggested that our novel stimuli were sufficiently discriminable through touch to allow us to test individuals without vision.

3. Experiment 2

As mentioned in Section 1, in this experiment we tested the role of early visual experience on haptic representation

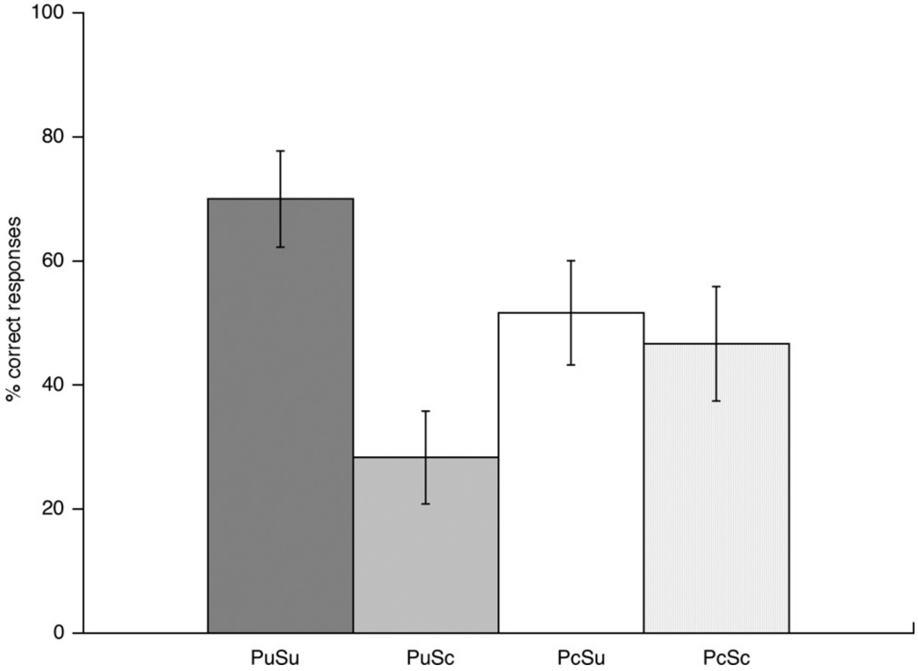

Fig. 2. Graph showing mean percentage correct responses in the sighted group as a function of the participants' learning position and scene orientation. The four conditions refer to the participants' position and the scene orientation after the learning phase: position unchanged (Pu) or position changed (Pc) and scene unchanged (Su) or scene changed (Sc). The error bars represent ± 1 standard error of the mean.

and updating of scenes of novel objects by comparing performance across two groups of blind participants; congenitally and late blind. The experimental protocol was the same as that described in the previous experiment.

Rossetti et al. and others have found that a delay between learning and test facilitates the construction of an allocentric, or global, representation of a tactile scene (manifested as qualitative changes in exploration procedures of the scene) and that such a representation can improve performance (Zuidhoek, Kappers, van der Lubbe, & Postma, 2003). Based on this previous literature, we provided constant a delay between learning and test in order to provide the optimal conditions for the coding of spatial scenes into more allocentric representations. We investigated whether spatial information was represented in an allocentric code by testing recognition performance across rotated scenes. Spatial updating performance was investigated by requiring the participant to move between learning the scene and test.

3.1. Method

3.1.1. Participants

Twenty-two blind individuals, recruited from various institutions (i.e. day-centres) for visually impaired persons in Paris, France volunteered to participate in our study. The majority of our participants reported to be totally blind and six reported experiencing light perception without being able to resolve shapes or other detailed visual information. Ten participants (7 female and 3 male) were congenitally blind and 12 participants (five females and seven males) were late blind. Most of the participants were in full-time employment or university students. The mean age per group was 37.3 years for the congenitally blind and 35.4 years for the late blind with no significant difference in age across the groups [$F(1,20) < 1$]. The extent of the visual impairment, blindness aetiology and other details including visual imagery ability are reported in Table 1. Visual imagery ability was a self-reported estimation by the participant in response to the experimenter's question of whether they could visually imagine objects. All other details about the nature of the visual impairment were confirmed by an appropriate staff member from the hosting institution.

All participants gave informed consent verbally and consent forms were co-signed by an appropriate witness. None of the participants reported any tactile impairments. The study was approved by the Trinity College, School of Psychology Ethics Committee.

3.1.2. Apparatus and stimuli

The same apparatus and set of stimuli used in Experiment 1 were again used here.

3.1.3. Design and procedure

The experiment was based on a $2 \times 2 \times 2$ mixed design with visual experience (congenitally or late blind participants) as between-subjects factor. Participants' position (unchanged 'Pu', or changed 'Pc') and scene orientation (0° 'Su'; or 45° 'Sc') were the within-subject factors. As in Experiment 1, participants performed four experimental conditions: PuSu, PuSc, PcSu and PcSc. All other details

Table 1
Details of the blind participants tested in this experiment

PP	Sex	Age	Blindness onset	Aetiology	Braille reading	Visual imagery	Residual vision
CB 1	F	27	Birth	Glaucoma	Y	N	
CB 2	M	19	Birth	Prenatal medicine intoxication	Y	N	
CB 3	M	24	Birth	Toxoplasmosis	Y	N	
CB 4	M	37	Birth	Postnatal hyper-oxygenation	Y	N	
CB 5	F	20	Birth	Eye malformation	Y	N	
CB 6	F	59	Birth	Glaucoma	Y	N	
CB 7	F	52	Birth	Prematurity	Y	N	
CB 8	F	29	Birth	Cataract	Y	N	
CB 9	F	56	Birth	Haemorrhage	Y	N	
CB 10	F	50	Birth	Prematurity	Y	N	
LB 1	M	45	21 years	Accident	Y	Y	
LB 2	F	19	2 years	Eye cancer	Y	Y	
LB 3	M	24	20 years	Glaucoma + retinal detachment	Y	Y	L
LB 4	M	24	19 years	Glaucoma	Y	Y	L
LB 5	F	56	6 years	Glaucoma	Y	Y	
LB 6	F	26	2.5 years	Eye cancer	Y	N	
LB 7	F	22	20 years	Glaucoma	Y	Y	L
LB 8	F	18	7 years	Retinoblastoma	Y	Y	L
LB 9	M	46	4 years	Rubella	Y	Y	L
LB 10	M	50	21 years	Accident	Y	Y	L
LB 11	M	40	18 years	Retinal detachment	Y	Y	
LB 12	M	55	7.5 years	Glaucoma + cataract	Y	Y	

Our participant groups are referred to as follows: 'CB' = congenitally blind and 'LB' = late blind. 'L' refers to residual sensitivity to light. Other labels used in the table are 'M' = male; 'F' = female; 'Y' = yes and 'N' = no.

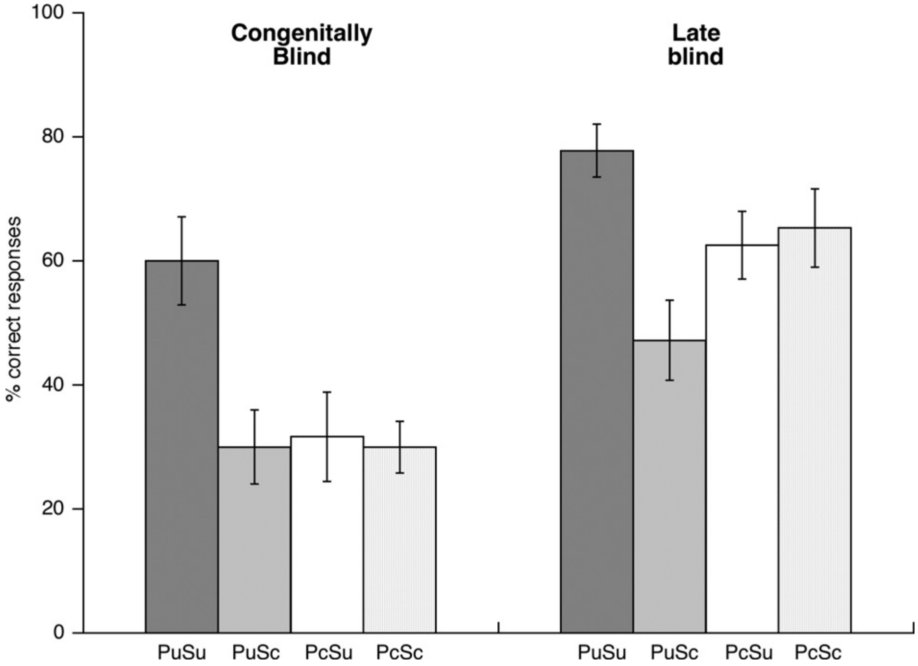

Fig. 3. Graph showing mean percentage correct responses across the two groups of blind participants, namely the congenitally and late blind groups as a function of the participants' learning position and scene orientation. The four conditions refer to the participants' position and the scene orientation after the learning phase: position unchanged (Pu) or position changed (Pc) and scene unchanged (Su) or scene changed (Sc). The error bars represent ± 1 standard error of the mean.

of the design and the procedure were the same as described in the previous experiment.

3.2. Results

The mean correct responses across all conditions are plotted in Fig. 3. Performance in all conditions was greater than chance (chance level was 1/7 or 14.3%) for both groups of participants. A three-way mixed ANOVA was performed on the correct responses with visual experience (i.e. none or early visual experience) as a between-subjects factor, and participants' position (Pu or Pc) and scene orientation (Su or Sc) as within-subject factors. We found a main effect of visual experience [$F(1,20) = 15.18$, $p < .001$] with better overall performance by the late than the congenially blind participants. We also found a main effect of scene orientation [$F(1,20) = 29.18$, $p < .001$], with better performance when the scene was not rotated than when it was rotated by 45°. Although marginal, the effect of participants' position was not significant [$F(1,20) = 3.39$, $p = .08$]. Most pertinently, there was a significant interaction between visual experience and the participant's position [$F(1,20) = 5.02$, $p < .05$]. This interaction was probably due to the congenitally blind group performing consistently worse across all conditions other than the condition when both the scene and participant were unchanged relative to the late blind group. Finally, we also found an interaction between participant position and scene orientation [$F(1,20) = 24.85$, $p < .001$]. No other interactions reached significance.

In order to understand the interactions better we analysed the data for each group separately. For the congenitally blind group we found a significant effect of participants' position [$F(1,9) = 6.83$, $p < .05$] and of scene orientation [$F(1,9) = 17.19$, $p < .005$]. There was also an interaction between participants' position and scene orientation [$F(1,9) = 6.18$, $p < .05$]. A post hoc analysis (Newman–Keuls) confirmed that performance to the condition PuSu (i.e. participants' position and scene unchanged) was significantly better than performance to the other three conditions [PuSc; PcSu; PcSc, $p < .05$] but there was no difference between these other three conditions (see Fig. 2). For the congenially blind participants, therefore, performance was best when the scene and participant were in the same position at test as learning otherwise there was a consistent cost in performance. For the late blind participants, on the other hand, we found evidence that they could update their representations with self-motion. For this group we found an effect of the scene orientation [$F(1,11) = 12.79$, $p < .005$] but no effect of participant position [$F(1,9) < 1$]. More importantly, we found an interaction between participant position and scene orientation [$F(1,11)=29.33$, $p < .001$], with post hoc analysis (Newman–Keuls) confirming that when the participants changed position (PcSu and PcSc) performance was significantly better than when the participant did not move but the scene was rotated (i.e. PuSc) [$p < .05$]. Thus, we found no evidence that congenitally blind participants could compensate for scene rotation with self-motion. Furthermore, both scene rotation and self-motion were associated with a cost in performance relative to when neither changed. Finally, even performance in the PuSu condition was worse in the congenitally blind group than the late blind group (see Fig. 3) suggesting inefficient representation of spatial information in the congenitally blind group.

3.3. Discussion

The results of this experiment suggest that visual experience plays an important role in the representation of spatial information in general and on the process of spatial updating of haptic representations of scenes in particular. Individuals deprived of vision from birth generally found the haptic scene recognition task more difficult than individuals who became blind later on in life (see also Gaunet et al., 1997). Moreover, we found that the cost in performance when the scene was rotated was not compensated by self-motion in the congenitally blind group, but that the late blind group could update their representations.

We were interested in knowing how performance compared across the blind participants (with and without early visual experience) in this experiment and sighted participants in the previous experiment. To that end, we conducted an analysis comparing performance across the three groups[1] and found a main effect of group [$F(2,29) = 5.85$, $p < .01$] with lower overall performance in the congenitally blind than either the late blind or sighted group (using a between subjects, post hoc Tukey HSD test, $p < .05$). We also found a main effect of scene rotation [$F(1,29) = 56.71$, $p < .01$] and an interaction between participant's position and scene orientation [$F(1,29) = 35.736$, $p < .01$]. Here, the interaction between group and participant position was not significant, although it was marginal [$F(2,29) = 2.601$, $p = .091$]. Planned, post hoc comparisons revealed that the source of this marginal interaction was a significant difference between performance to the changed and unchanged position of the participant in the congenitally blind group only ($p < .02$) but not in either the late blind ($p = .781$) or the sighted group ($p = .992$). These analyses suggest that congenitally blind differed in both the nature and updating of spatial representations relative to participants with visual experience.

4. General discussion

In our experiments, we found evidence that both sighted and late blind participants could efficiently update representations of novel scenes encoded through touch. Congenitally blind participants, on the other hand, were compromised on their ability to spatially update a learned scene as they moved around. Moreover, our results indicated that the representation of spatial information in general was relatively impaired in the congenitally blind group but that overall performance was similar across sighted participants and those with early visual experience. These results imply that visual experience is necessary both for efficient representation and updating of scenes with observer movement, although the extent to which updating is affected by the poor representation of spatial information is not clear from the current data. Therefore, the possibility remains that spatial updating processes are intact but optimal updating performance is compromised by the relatively poor representation of spatial information in persons without visual experience.

Although performance in the congenitally blind group was poor relative to both the late blind and sighted participants, haptic scene recognition performance was qualitatively similar to that found in the late blind group and the sighted group in Experiment 1 and in our previous study with sighted participants (Pasqualotto et al., 2005). That is, a cost in performance to a rotated scene relative to a stationary observer was found in all participant groups. This finding suggests that the mechanisms for representing scenes through touch are similar across persons with and without visual experience. Moreover, view-dependent performance is generally considered evidence for egocentric representations of objects or scenes (see e.g. Diwadkar & McNamara, 1997; Newell et al., 2005) since recognition is dependent on changes in the objects' positions relative to the observer, not just to inter-object changes. Our findings here are contrary to some other studies which suggest that a delay between learning and test of spatial arrays generally involves a change from an egocentric representation to a more allocentric representation (see e.g. Zuidhoek et al., 2003). We found no evidence that the quality of scene recognition performance was different across groups, since all showed effects of view-dependency with scene rotation when the observer was stationary. However, it is possible that the manner in which the information was encoded between learning and test differed across groups (see e.g. Rossetti & Régner, 1995; Rossetti et al., 1996), and this difference contributed to the poor performance in the congenitally blind group. Although it is not possible to determine these differences in the current experiments, our future plans include an investigation of the tactile scan paths used in scene perception across sighted and blind groups.

Our findings may seem discordant from those reported by Hollins and Kelley (1988, Experiment 4), which suggested no effect of visual deprivation on a spatial updating task. The discrepancies between the tasks may, however, account for the different findings. For example, Hollis and Kelley found that when congenitally blind participants could touch the apparatus (i.e. the supporting table) after the learning phase, then this provided a useful reference frame to match with the memory of the scene and conse-

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[1] These direct comparisons should be treated with some caution as there were methodological differences between the experiments. For example; we used a curtain in Experiment 1 but not in the second experiment; the participants in Experiment 1 were not blindfolded therefore could avail of any non-informative visual cues to perform the task; sighted participants were slightly older than the blind participants.

quently may have improved performance. In contrast, although our congenitally blind participants could also touch the platform and its edges, most of the haptic exploration was concentrated on the object stimuli and the supporting platform and its edges were seldom explored. Task difficulty may also account for the differences in findings across these studies. For example, the stimuli used by Hollins and Kelley were familiar objects of different materials that could be easily named, whereas our stimulus set were less discriminable and could not be verbalised.

We also found evidence to suggest that even without a change in position of the participant or the scene (i.e. in the PuSu condition), performance was better in the sighted and late blind groups than the congenitally blind group (70% and 77% versus 60%, respectively). This finding suggests that the efficient representation of spatial information is compromised in the absence of visual experience. Other studies in object recognition have reported evidence consistent with the idea that visual experience is necessary for efficient spatial perception (e.g. Gaunet et al., 1997; Graven, 2004; Heller, 1989; Heller, Wilson, Steffen, Yoneyama, & Brackett, 2003), although some other studies suggest that good spatial skills and understanding can be readily acquired by congenitally blind persons. For example, Kennedy (2000) has demonstrated that a congenitally blind person with drawing experience can represent perspective in two-dimensional drawings. Moreover, the literature on the role of visual experience on large-scale spatial understanding generally accords with the role played by practice on spatial tasks to, for example, allow congenitally blind to travel independently (Haber, Haber, Levin, & Hollyfield, 1993; Loomis et al., 1993).

The extent to which explicit learning strategies can be applied to spatial updating rather than spatial representations per se is, however, unclear. If vision is necessary for spatial updating, then congenital blindness would result in a significant and permanent spatial impairment with observer motion, as indeed our findings suggest. Moreover, this would imply that the non-visual senses cannot provide sufficient cues to develop efficient spatial understanding. However, several studies have reported that touch, audition and even olfaction can efficiently convey spatial information (Klatzky, Lippa, Loomis, & Golledge, 2002, 2003; Porter, Anand, Johnson, Khan, & Sobel, 2005). Additionally, studies on sensory substitution (see Bach-y-Rita, 1972 for a review on the early studies; Bach-y-Rita & Kercel, 2003), have suggested that, with practice, information about the shape and position of distal objects could be efficiently conveyed to blind people (e.g. by using a tactile feedback device positioned either on the persons' back or tongue). Moreover, by using tactile-visual sensory substitution devices, individuals who have never seen throughout their life can learn to experience both perspective in objects and size constancy, which are generally considered attributes of the visual perception only. Thus the possibility remains that with extensive practice on spatial updating tasks, congenitally blind participants could learn to adopt strategies that would allow them to update scene information as they move around. For example, the addition of a tactile reference frame (e.g. a rectangular tactile frame) may facilitate the integration of the cues generated by the participants' movement to allow for efficient updating (see e.g. Millar & Al-Attar, 2004). Without such task-specific practice or the addition of external cues, however, it seems that the absence of visual experience compromises the spontaneous acquisition of updating procedures.

Several recent findings reported by Brigitte Röder and colleagues have suggested that vision may be necessary to integrate spatial information across the senses (see also Zuidhoek, Visser, Bredero, & Postma, 2004). This idea is supported by the finding that congenitally blind individuals are less susceptible to an auditory-tactile 'Shams illusion' (Shams, Kamitani, & Shimojo, 2000): participants were required to report the number of tactile stimulations whilst ignoring the more numerous tones they heard (Hötting & Röder, 2004). In general the number of taps experienced is influenced by the number of tones heard, but congenitally blind individuals seem to be unaffected by this illusion. Similarly, Röder et al. (2004) reported that a crossed-hand posture did not produce any cost in judgements of the temporal order of tactile stimulation to the hands of congenitally blind participants compared to blindfolded sighted and late blind participants. Typically, such a posture shows a robust cost on temporal order judgements in blindfolded sighted participants (e.g. Shore, Spry, & Spence, 2002). In light of these findings, we speculated that vision is also necessary for multisensory integration in the representation and updating of spatial information such as haptic scenes.

Exactly when vision plays a role in spatial information processing across modalities is, however, unclear. For example, visual experience could facilitate the representation of spatial information, or the updating of this information or both. It is possible that vision either provides the reference frame (or precision) to which spatial information from other modalities is encoded or it facilitates transfer of co-ordinate information across modalities. The absence of vision could therefore result in a level of uncertainty in the representation, which then results in poor spatial updating. On the other hand, complete visual deprivation may impair the integration of information represented in the haptic modality with the cues produced by self-motion (e.g. vestibular, kinaesthetic and/or proprioception) that allows for efficient spatial updating. Our findings are consistent with the result that even in the absence of visual cues during the task, previous experience with visual information is sufficient to allow for efficient representation and updating of relatively small-scale spatial information: in the late blind group, haptic scene representation is remarkably similar to that of sighted individuals in Experiment 1 in terms of overall performance and the typical cost with scene rotation (see also Pasqualotto et al., 2005). This suggests that vision plays an important role at the level of representing spatial information across modalities. If practice can affect better recognition performance in the congenitally blind group (as previous studies suggest) then it remains to be seen if spatial updating is then consequently improved.

Although the role of vision in rat navigation in familiar environments does not seem to be crucial (e.g. Save et al., 1998) here we found that the absence of visual experience impairs updating in an unfamiliar spatial task involving peripersonal space in humans. Previous studies on spatial updating in humans in relatively small-scale space have implicated the parietal cortex in this task (Merriam et al., 2003). However, most previous research on the effect of visual deprivation on perception has focused on investigating the consequent effects on primary visual and dorsal cortical areas, whereas studies on the role of visual impairment on parietal functioning are comparatively rare. Nevertheless, parietal functioning has been found in the updating of both visual and auditory sensory input in the monkey as a function of eye movements (Andersen, 1997), suggesting that this area is a likely candidate for the role of updating across all the senses in humans. Moreover, our findings suggest that normal activation in the parietal cortex may be impaired in the absence of visual input. This suggestion is supported by a study reported by Hyvärinen, Hyvärinen, and Linnankoski (1981) that early visual deprivation affects the organization of cells in the PPC by reducing the amount of activation from multisensory inputs. Additional evidence for the role of vision in normal brain development has been provided by Wallace and colleagues (Wallace, Hairston, & Stein, 2001; Wallace, Perrault, Hairston, & Stein, 2004): they found that the pattern of neuronal activity in the superior colliculus of dark reared animals to temporally or spatially coincident inputs from different modalities was altered compared to non-light deprived animals. Moreover, the SC cells in visually deprived animals responded to unimodal inputs only, again suggesting a role of vision in multisensory integration.

Given that the absence of visual experience produces a cost in the representation and updating of spatial scenes, we suggest that visual experience influences spatial representation and updating because it influences multisensory integration, possibly by providing precision in the spatial reference frame through which other senses are encoded. Moreover, vision may affect spatial perception through the alteration of the brain structures involved in multisensory integration and spatial updating, most likely the parietal cortex, although the precise neural correlates of multisensory spatial updating have yet to be elucidated.

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