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Visual experience facilitates allocentric spatial representation

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Abstract

Representing the position of the objects independently from our own position is a fundamental cognitive ability. Here we investigated whether this ability depends on visual experience. Congenitally blind, late blind and blindfolded sighted participants haptically learnt a room-sized regularly shaped array of objects, and their spatial memory was tested to determine which spatial reference frame was used. Crucially, the use of an object-based reference frame requires representing the regular structure of the array. We found that blindfolded sighted and late blind participants, that is those with visual experience, showed a preferential use of the object-based or 'allocentric' reference frame. On the contrary, congenitally blind participants preferred a self-based, or egocentric, reference frame. This suggests that, due to its developmental effect on the multisensory brain areas involved in spatial cognition, visual experience is necessary to develop a preference for an object-based, allocentric reference frame.

Abbreviations: 'CB', congenitally blind; 'LB' late blind; 'S' sighted.

Introduction

McNamara and colleagues [1] reported the counterintuitive result that the representation of a regular array of objects was based on the intrinsic structure of the array (i.e. object-based, or allocentric, rows-and-columns grid pattern), rather than on the egocentric viewing position (see also [2] for equivalent results within the peripersonal space in arm's reach). More precisely, from a given viewing position, participants viewed a set of objects disposed on the room's floor and then their spatial memory was tested in a Judgement of Relative Direction task (JRD) where they imagined being close to a given object within the array, being oriented toward a second object and pointing in the direction of a third one (i.e. heading). For example, "Imagine that you are at the clock, facing the shoe, point to the jar"). Surprisingly, results showed that participants were more accurate for headings aligned with the intrinsic structure of the array than with the familiar viewpoint. This suggests that participants could extract the grid pattern of the array and use it to store the position of the objects in their spatial memory and, consequently, they performed the JRD task better when the tested headings matched the grid pattern. Here we adapted the method by McNamara and colleagues [1] and tested congenitally blind, late blind, and blindfolded sighted participants to investigate whether the ability using an allocentric reference frame is subject to visual experience or whether it is innate.

Additionally, the current study can shed a light on the role of a critical period for developmental vision on spatial cognition and brain organisation [3]. In fact, although it is an established opinion that blindness sharpens the remaining modalities [4-5], discordant results have been reported by studies investigating spatial cognition in blind individuals. Thus, some researchers found results suggesting that congenital blindness prejudices the complete development of spatial cognition [6-7]. On the contrary, other authors reported data suggesting that visually impaired people can perform spatial tasks at the same level as sighted

[8-9]. Yet, a few studies comparing the use of spatial reference frames across blind participants may suggest that visual experience is crucial for spatial tasks requiring the use of allocentric spatial representation, while egocentric spatial abilities should be preserved [10-11].

Along these lines, we created a somatosensory task (i.e. based on haptics, proprioception and vestibular cues) where two groups of blind and one group of blindfolded sighted participants were led by the experimenter to explore objects arranged in a regular array and then they underwent a JRD task. If visual experience is crucial for developing allocentric spatial representation, and thus for the ability of perceiving the grid-pattern of the array, we would find that participants without visual experience (congenitally blind) are less precise in JRD involving headings parallel to the grid-pattern (i.e. that the allocentric reference frame is not exploited). Yet, they will be more accurate in JRD involving headings parallel to the routes walked during the array exploration, that is, to the participants' egocentric representation of the array. On the other hand, participants possessing visual experience (late blind and blindfolded sighted) are expected to exhibit the opposite results: more accurate performance for allocentric headings, and poorer for egocentric.

Method

Participants

We tested 20 blind participants recruited through local blind institutions. Ten were congenitally blind (CB), five males and five females, with a mean age of 43 (16.23 SD).Ten were late blind (LB), five males and five females, with a mean age of 43 (12.18). Finally, we tested a group of ten matching blindfolded sighted individuals (S), five males and five females, with a mean age of 43.4 (9.05) (see Table 1 for details). None reported any motor

impairment. All participants signed a consent form approved by the local Research Ethics Committee. Participants received £10 for their participation.

[Table 1 about here]

Apparatus

Common objects were arranged inside a roughly rectangular room about 12.5 by 9 m (see Figure 1). Each object was placed on a 90cm tall stool to facilitate haptic exploration. Between each stool there was a distance of about 1.5 m. A chair placed about 2 m from the closest object (brush) was the starting-point of each exploration.

During the JRD task, participant used a LogiTech™ 3DPro joystick connected to a Dell™ Latitude E5510 laptop running a MatLab™ program that recorded pointing angles and reaction times. The pointing task took place in a nearby room sized 3 by 2 m. Sighted participants were blindfolded throughout the experiment by a MindFold™. As no blind participant had more than light/darkness sensitivity none of them wore the blindfold.

[Figure 1 about here]

Procedure

The experiment consisted of two phases, learning and testing. Sighted participants were blindfolded. Then participants were guided into the 'learning' room where they familiarised with the use of the joystick. Led by the experimenter, participants began the exploration of the array. Objects were explored one-by-one, with participants being led along straight routes back-and-forth from the starting-point to each object (see [12] for similar learning procedure). Yet, to highlight the intrinsic structure of the array, the exploration order

proceeded by horizontal rows (e.g. starting-point, pan, starting-point, slipper, starting-point, brush, etc.). To ensure that participants learned the array, after the exploration they were asked to verbally recall the objects by following the exploration order. This procedure ended when participants could correctly recall all the objects twice consecutively without help (on average it took 3-4 attempts, maximum 5).

Led by the experimenter, participants reached the 'testing' room where, before using the joystick, they received a sheet of paper reporting a bird's eye-view 'tactile map' of the array (see [13]). This was aimed to promote an allocentric spatial representation. Thus, this simple sheet had seven little holes representing the seven objects arranged as in the learned array, and one hole representing the starting-point. By using both hands and led by the experimenter, participants explored the map by following the learning order, and then they could freely explore the map for about 1 minute.

During the JRD task, the experimenter read the statements that appeared on the computer screen, for example: "Imagine that you are at the book (brief pause), facing the bottle (brief pause), point to the pan". Then a sound indicated that the joystick could be aimed, as quickly and as accurate as possible, towards the target object. The reaction time recording began when the sound was emitted. After each pointing a new statement was read by the experimenter. There were 48 random trials, six for each of the eight headings that had to be imagined during the task. Four headings were aligned to the routes walked during the array exploration (315°, 225°, 135° and 45°), whilst four were aligned to the internal structure of the array (0°, 270°, 180° and 90°), see Figure 1. Horizontal pointing errors in degrees and reaction times were recorded. The entire experiment took about 50 minutes to complete.

Results

Average pointing errors and reaction times were analysed in a three-way mixed design ANOVA with Visual Status (CB, LB, and S) as between-subjects condition, the Reference Frame underlying the headings (egocentric and allocentric) and the Imagined Headings ($0°$, $45°$, …, and $315°$) as within-subjects conditions.

Pointing error analysis revealed no effect of the Visual Status [$F_{(2,27)}=1.18$, $p=.322$] indicating that overall the three groups performed the task equally well. There was a significant effect of the Reference Frame [$F_{(1,28)}=7.84$, $p=.009$] showing that in general allocentric orientations were better performed (i.e. better performed by both LB and S, see below). Overall the single Imagined Headings did not produce a significant effect [$F_{(7,22)}=2.68$, $p=.052$]. Interestingly, there was a significant interaction between Visual Status and Reference Frame [$F_{(4,25)}=28.58$, $p=.000$], indicating that CB performed better egocentric trials, while LB and S were better in allocentric trials (see Figure 2). Additionally, the Fischer post-hoc analysis showed that: in egocentric trials CB performed better than LB and S, while in allocentric trials LB and S performed better than CB [all $p<.05$]. The interaction between Visual Status and Imagined Heading was not significant [$F_{(10,19)}<1$] nor the interaction between the Reference Frame and the Imagined Heading [$F_{(7,22)}=1.46$, $p=.231$] was significant. Finally the interaction across Visual Status, Reference Frame and Imagined Heading was significant [$F_{(12,17)}=3.28$, $p=.006$], showing that for a given group some particular headings were better performed. Specifically, CB were more accurate with the $135°$ and $315°$ Imagined Headings (which are egocentric), LB were better with the $0°$ and $90°$ Imagined Headings (allocentric), while S where more accurate with the $0°$ and $270°$ Imagined Headings (allocentric).

Reaction times were analysed with the same design as pointing errors. There was a significant effect of the Visual Status [$F_{(2,27)}=3.46$, $p=.046$], indicating that S were faster than the blind groups. The effect of the Reference Frame was not significant [$F_{(1,28)}<1$].

Overall no single Imagined Heading affected the reaction times [$F_{(7,22)}=2.57$, $p=.060$]. Again there was a significant interaction between Visual Status and Reference Frame [$F_{(4,25)}=11.42$, $p=.000$] (see Figure 3). The Fischer post-hoc analysis showed that CB were faster in egocentric trials than allocentric, while LB were faster in allocentric than egocentric. Finally S were faster than CB in both allocentric and egocentric trials [all $p<.05$]. The interaction between Visual Status and Imagined Heading was significant [$F_{(10,19)}=4.04$, $p=.001$] indicating that some Imagined Headings were faster performed by CB (45° and 135°), others were faster performed by LB (90°, 180° and 270°), and others were faster performed by S (0°, 90°, 180° and 270°). The interaction between the Reference Frame and the Imagined Heading was not significant [$F_{(7,22)}=1$, $p=.396$] nor the interaction across Visual Status, Reference Frame and Imagined Heading was significant [$F_{(12,17)}=1.20$, $p=.310$].

Thus, both the results relative to the pointing errors and the reaction times support the hypothesis that Visual Experience dictates the preference for a given type of spatial representation. The murkier results associated to the reaction times are likely to be due their higher variability, which reflect different response 'styles' across participants (e.g. more or less impulsive).

[Figure 2 about here]

[Figure 3 about here]

Discussion

Our results suggest that participants possessing visual experience (LB and S) were able to extract the structure of the array and to use it during the spatial memory task. Thus they better performed on trials requiring imagined headings aligned to the structure of the array.

Conversely, participants without visual experience (CB) were better at using the self-referenced cues arising from the spatial exploration to perform the memory task (i.e. idiothetic cues, see [14]). Thus they better performed on trials requiring imagining headings aligned with the explorative routes they had walked.

Thus we found support for the hypothesis that visual experience is necessary to develop and use an allocentric spatial representation, which CB find quite difficult to achieve [10]. It is important to note that here we claim that visual experience determines the preference for a given type of spatial representation (i.e. it facilitates its adoption). In fact, past studies reported the CB participants were able to carry out path integration and allocentric spatial representation [8-9]. Therefore, we may find that by increasing the exposure to the array CB participants would improve their performance in allocentric trials.

Additionally, our results on sighted participant extend earlier findings on vision [1] to the somatosensory modality –i.e. that S participants used the intrinsic structure of the array. Differently from McNamara and colleagues [1] we found that our sighted participants are less accurate in the pointing task their sighted participants who visually learned the array. This can be explained by the fact that learning the array by somatosensation represents an effortful and error prone serial process [15]. In fact, vision has the ability to convey simultaneous information about different objects, which is particularly advantageous for objects laying outside the peripersonal space, while by using somatosensation the spatial relations among objects have to be patiently constructed [15-16].

Finally our results extend a previous study that examined spatial reference frames in auditory peripersonal space to extra-personal space [17]. In that study, CB, LB, and S participants judged the spatial occurrence of sounds within peripersonal space (perceptive task). Our study instead examined the mental representation of an extra-personal spatial array

of objects in memory. In both experiments, CB participants preferred an egocentric representation.

Aside its influence on non-visual areas [18], the role of developmental vision on spatial cognition and on its underlying brain structures can be clarified by the studies investigating the role of visual experience on brain areas devoted to multisensory integration. For example, Wallace and colleagues reported that visual experience is necessary to develop multisensory neurons [19]. Accordingly, Röder and colleagues [20] found that congenitally blind participants were less affected by an auditory-tactile counting illusion (i.e. tactile taps and beeps). Crucially, the effect of visual experience on multisensory integration was also found in spatial tasks, for example CB are not affected by hands crossing in a temporal order judgement task [21]. Additionally, the role of visual experience was shown in spatial updating tasks [6, 22]. Recent studies began to report effects of visual experience on the multisensory brain areas involved in spatial tasks, such as the hippocampus [23-24] and the posterior parietal cortex [25].

This suggests that during the initial years of the human life visual experience exerts its effects on the brain areas involved in spatial processing and multisensory integration, supporting the hypothesis that the use of an allocentric reference frame to remap multisensory spatial inputs is not innate but its development requires visual experience [10].

Conclusion

In our study we found evidence that visual experience triggers the preference for a given type of spatial representation. Specifically, although people with visual experience preferentially represent object locations with an allocentric reference frame, those without visual experience instead preferentially represent object locations with an egocentric reference frame. This is

supported by recent studies reporting an effect of visual experience on brain areas involved in multisensory integration for spatial cognition. Finally, our results try to provide a broader interpretation of the contradictory literature on the effect of blindness in spatial cognition by underlining the role of the reference frame required for a given spatial task.

Acknowledgements

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Captions

Figure 1: A depiction of the experimental setup with the eight headings. The underlined headings are the allocentric (0°, 270°, 180° and 90°) while the remaining are the egocentric (315°, 225°, 135° and 45°).

Figure 2: Mean pointing errors in degrees across the three experimental groups for each of the eight headings (the underlined headings are the allocentric ones); filled squares indicate congenitally blind participants; dashed circles are the late blind participants; empty circles are the blindfolded sighted participants. Error bars represent the standard error.

Figure 3: Mean reaction times in seconds across the three experimental groups for each of the eight headings (the underlined headings are the allocentric ones); filled squares indicate congenitally blind participants; dashed circles are the late blind participants; empty circles are the blindfolded sighted participants. Error bars represent the standard error.

Table 1: Details of the participants; 'Educ.' indicates the level of education (University or Secondary). 'Y' means 'yes' and 'N' means 'no', while 'L/D' means 'light/darkness' sensitivity and, if relevant, in which eye (left of right). Aetiology abbreviations: 'RoP', retinopathy of prematurity; 'Retinobl',retinoblastoma; 'Cong', congenital; 'Cat', cataracts; 'Gla',glaucoma; 'RP', retinitis pigmentosa; 'Ret deg' retinal degeneration.
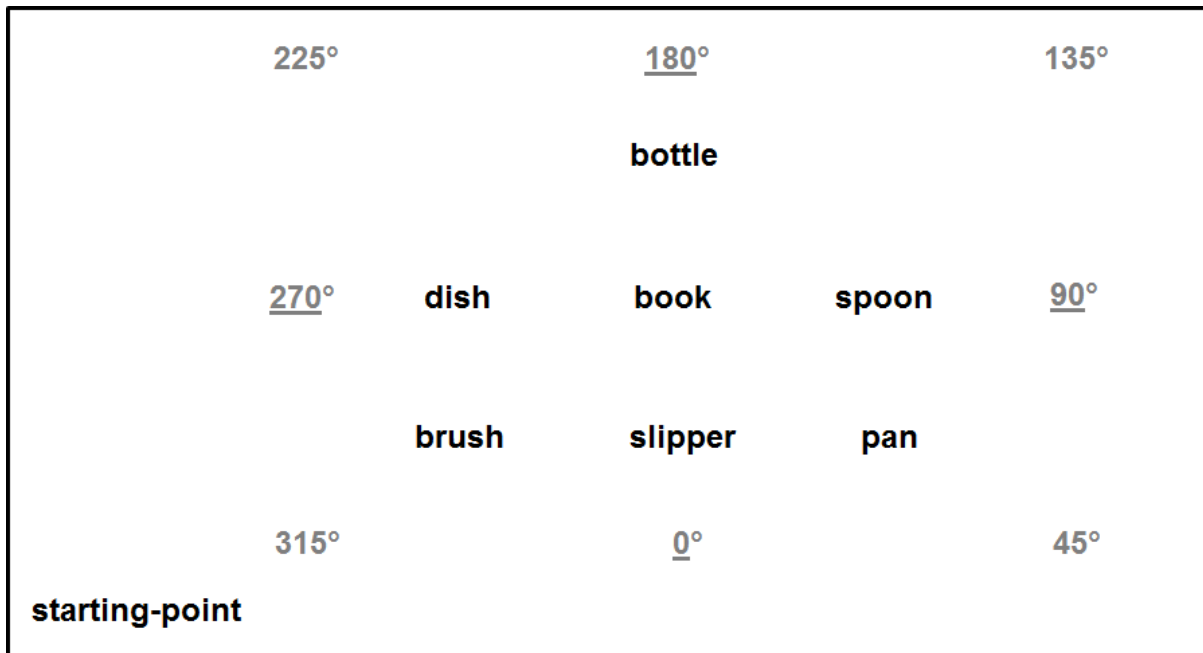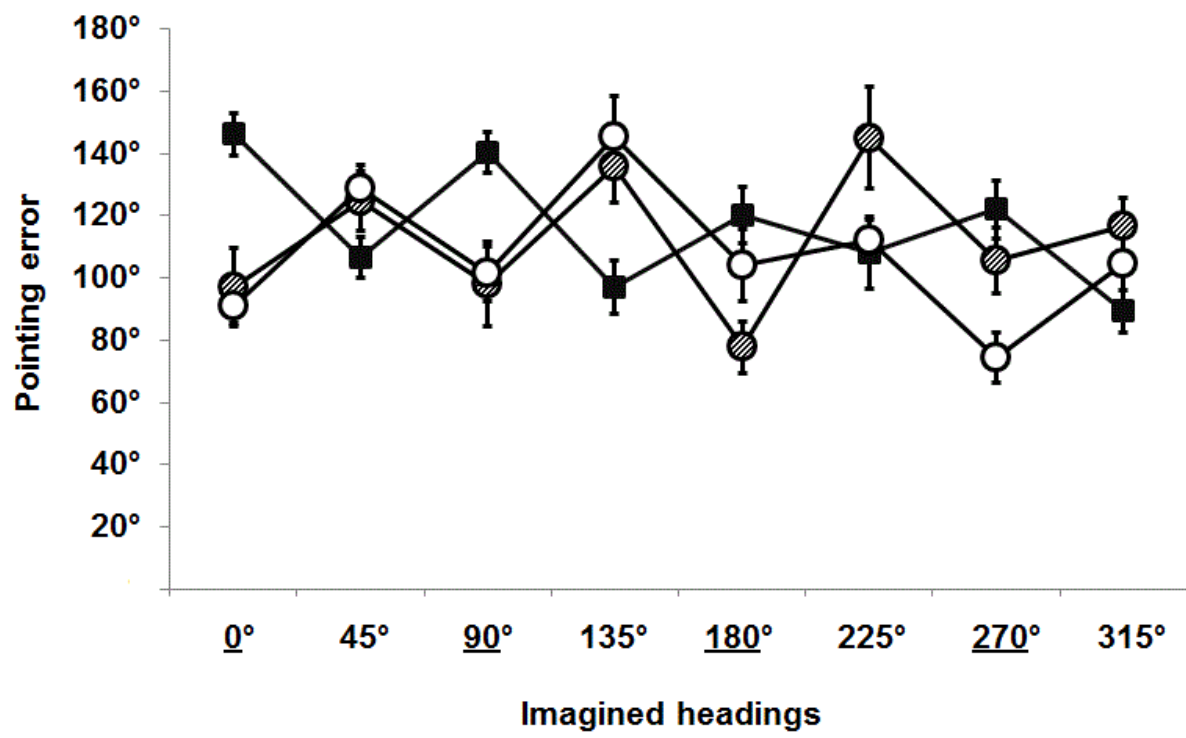
Figure 1

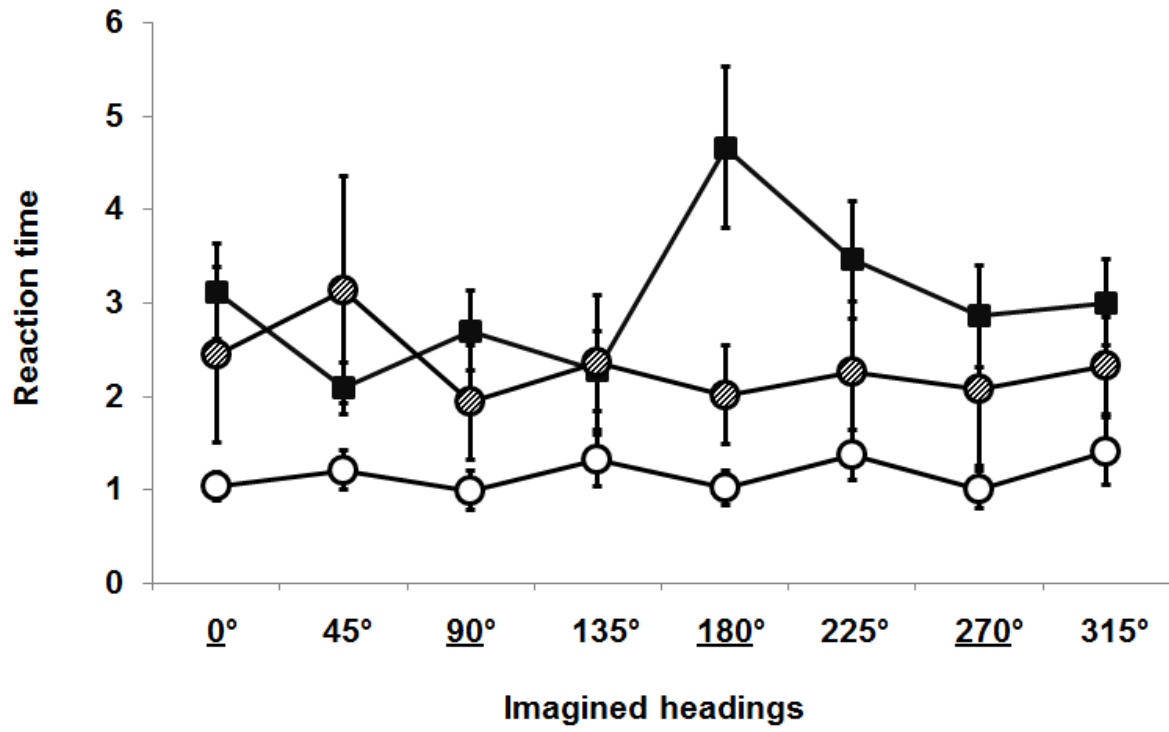| 225° | | 180° | | 135° |
		bottle		
270°	dish	book	spoon	90°
	brush	slipper	pan	
315°		0°		45°

starting-point

Figure 2

Figure 3

Table 1

	Sex	Age	Hand	Educ.	Onset	Aetiology	Braille reading	Visual imagery	Residual vision
CB1	M	59	Rx	Uni.	Birth	RoP	Y	N	N
CB2	M	58	Rx	Uni.	Birth	Retinobl	Y	N	N
CB3	F	26	Rx	Sec.	Birth	Genetic retinal dysplasia	Y	N	N
CB4	F	27	Rx	Uni.	Birth	Optic nerve did not develop	Y	N	L/D
CB5	F	27	Rx	Sec.	Birth	Cong Cat + Gla	Y	N	L/D
CB6	M	63	Rx	Sec.	Birth	RoP	Y	N	N
CB7	F	27	Lx	Uni.	Birth	Cong gla + Cat	Y	N	N
CB8	F	35	Rx	Uni.	Birth	Cong gla	Y	N	L/D
CB9	M	46	Rx	Sec.	Birth	RoP	Y	N	N
CB10	M	62	Rx	Sec.	Birth	RoP	Y	N	N
LB1	F	38	Rx	Uni.	21	Optic nerve atrophy	Y	Y	L/D
LB2	M	22	Rx	Uni.	12	Gla	Y	Y	L/D
LB3	M	55	Rx	Sec.	2	Measles	Y	Y	N
LB4	M	58	Rx	Sec.	50	RP	N	Y	N
LB5	M	44	Rx	Uni.	32	Retinal degeneration	Y	Y	L/D
LB6	F	44	Lx	Sec.	21	Diabetic retinopathy	N	Y	N
LB7	F	54	Lx	Uni.	2	Retinobl	Y	Y	N
LB8	M	24	Rx	Sec.	3	Optic nerve atrophy	Y	Y	L/D (Lx)
LB9	F	44	Rx	Sec.	25	RP + Retinal dystrophy	Y	Y	L/D (Lx)
LB10	F	47	Rx	Sec.	11	Retinal degeneration	Y	Y	N