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Vision shapes tactile spatial perspective-taking

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Abstract

Information from the environment can be perceived according to egocentred or decentred spatial perspectives. Different spatial perspectives can be adopted when perceiving not only visual, but also auditory or tactile information. As vision may be dominant in setting up spatial information processing, visual loss might affect perspective taking in other sensory modalities. The present study investigated the influence of vision on the perspective that is adopted naturally and the influence of visual experience on the ability to switch between perspectives in the tactile domain. Participants with varying degrees of visual experience (early-blind, late-blind, blindfolded-sighted and sighted) completed a tactile recognition task of ambiguous letter stimuli (b, d, p, and q) presented on the body, for which three perspectives can be adopted (trunk-centred, head-centred and decentred). The participants were first free to adopt any perspective they wanted, before either the same or a different perspective was imposed. The results showed that both a temporary and permanent lack of vision promotes spontaneous adoption of egocentred spatial coordinates, anchored to the head. Moreover, more decentred coordinates were adopted by the blindfolded-sighted compared to the early and late-blind, suggesting that blindness reduces the adoption of decentred perspectives. Finally, the early-blind exhibited a greater cost of switching perspectives compared to the sighted, suggesting that early visual experience is important for flexible perspective-taking. Overall, our study reveals that vision shapes both the naturally adopted perspective and the flexibility to change perspective.

Keywords: Spatial Cognition; Vision; Blindness; Tactile Perception; Spatial Perspective-taking; Graphesthesia

1. Introduction

Perceptual information can be represented relative to oneself (egocentred spatial perspective) or relative to an external location (decentred spatial perspective). Spatial representations are typically thought of as visual (Heller & Kennedy, 1990), yet other sensory modalities (e.g. audition, touch, olfaction, as well as kinaesthetic feedback) are also extensively involved in spatial representations (Thinus-Blanc & Gaunet, 1997). However, if vision is dominant in shaping spatial knowledge, then an absence of visual experience may greatly affect the ability to perform spatial tasks, including perspective-taking, using other sensory modalities such as audition or touch (for a review see Pasqualotto & Proulx, 2012). How a loss of vision influences the processing of information across spatial perspectives has been subject to much debate (Cattaneo et al., 2008; Thinus-Blanc & Gaunet, 1997). Previous findings suggest that those with less than three years of visual experience (i.e. the early-blind) rely more on information from egocentred rather than decentred perspectives in navigation tasks (Chiesa, Schmidt, Tinti & Cornoldi, 2017; Iachini, Ruggiero, & Ruotolo, 2014; Pasqualotto, Spiller, Jansari, & Proulx, 2013; Rossetti, Gaunet, & Thinus-Blanc, 1996), suggesting that there is a critical period in visual development that shapes spatial perception. However, other findings suggest that visual experience is not necessary for efficient spatial cognition, with similar performance observed for congenitally blind and sighted individuals (Haber, Haber, Levin, & Hollyfield, 1993; Loomis et al., 1993; Tinti, Adenzato, Tamietto, & Cornoldi, 2006; Tinti et al., 2018).

In the tactile modality, it is well established that in order to localise a stimulus in space, tactile information is ‘remapped’ from a somatotopic reference frame into an external reference frame not anchored to the body. This involves a recoding of spatial information from an anatomical (where on the body was a stimulus) to an external reference frame (where in external space was a stimulus). Evidence for tactile remapping has shown that changes to limb posture, such as crossing the hands, impairs performance when judging the temporal order of tactile stimuli applied to the hands (Harrar & Harris, 2010; Shore, Spry, & Spence, 2002; Yamamoto & Kitazawa, 2001). This crossed hand effect is attributed to the conflict between the anatomical and external reference frames used to localise the tactile stimuli. Importantly, the crossed hands effect is not observed in congenitally blind individuals, suggesting that early visual experience is important for the development of tactile spatial coding (Röder, Föcker, Hötting, & Spence, 2008; Röder, Rösler, & Spence, 2004).

Thus, how vision affects spatial coding during tactile localisation and spatial navigation has been investigated, however little is known about the role of vision in spatial coding during tactile object perception. This is all the more crucial as touch is the main window to object perception for the visually impaired. Previous research has shown that tactile object and scene recognition undergoes a process of ‘spatial updating’ when novel haptic scenes are encountered (Newell, Ernst, Tjan, & Bühlhoff, 2001; Pasqualotto, Finucane & Newell, 2005). One study (Pasqualotto & Newell, 2007) compared sighted, congenitally and late blind participants on a task requiring the recognition of a previously learned haptic scene. The scene consisted of novel objects presented across the same or different orientations as previously learned whilst the participant either remained in the same position or moved to a new position relative to the scene. Haptic scene recognition was worse in the congenitally blind group, who were also unable to compensate for the cost in scene rotation with observer motion, suggesting that vision plays an important role in representing and updating spatial information encoded through touch. Importantly, tactile object perception also depends on the spatial perspective adopted to interpret information. Recent findings in sighted individuals have shown that they not only differ in the spatial perspectives that they naturally adopt, but also in the flexibility with which they can switch between spatial perspectives when perceiving tactile stimuli on the body (Arnold, Spence, & Auvray, 2016), in line with recent research on the flexibility of switching between visual perspectives (Samuel, Roehr-Brackin, Jelbert, & Clayton, 2019). However, so far, little is known about the role of early versus late vision loss on both adopting and, importantly, the flexibility in switching tactile spatial perspectives.

Only one early study (Shimojo, Sasaki, Parsons & Torii, 1989) investigated the role of vision in tactile spatial perspective taking. Eight early-blind individuals were asked to recognize ambiguous letters manually drawn by the experimenter on various body surfaces. Similar patterns of egocentred and decentred perspectives were adopted by the early-blind and sighted controls. However, that study did not compare the effect of different degrees of visual loss on tactile perspective taking (effects of early versus late blindness, or a temporary loss of vision), nor the flexibility of switching perspectives.

To investigate the influence of vision on spatial perspective taking, participants completed the Graphesthesia task (Arnold et al., 2016; Arnold, Spence, & Auvray, 2017) which first established the perspective spontaneously adopted on tactile stimuli and then tested the ability to switch between natural and unnatural perspectives (see Figure 1.A). The first aim was to

investigate effects of vision on the spatial perspective spontaneously adopted to perceive ambiguous tactile stimuli. Individuals with less than three years of visual experience (early-blind), more than three years of visual experience (late-blind), a temporary loss of vision (blindfolded-sighted) or full vision (sighted individuals) were compared on which spatial perspectives they spontaneously adopted to recognise tactile stimuli. This allowed investigating the role of an early, late, or temporary loss of vision on the perspective one *naturally* adopts to perceive tactile stimuli. The second aim was to investigate whether visual experience affects the ability to flexibly switch between perspectives. To do this, the cost of switching spatial perspectives was compared across early-blind, late-blind and sighted participants.

2. Methods

2.1. Participants

Sixty-nine blind adults were recruited for the experiment. Nine participants were subsequently excluded, one due to an error during data collection and eight for having below 50% consistency in Session 1¹. After exclusion, the early-blind group (less than three years of visual experience) included twenty-eight participants (16 females, 23 right-handed) and the late-blind group included thirty-two participants (14 females, 28 right-handed). Forty-five adults with normal or corrected-to-normal vision were recruited for the blindfolded-sighted group. Seven of them were excluded for low consistency in Session 1 (<50%), leaving thirty-eight blindfolded-sighted participants (22 female, 37 right-handed). A sample size calculation using G*Power 3.1 (Erdfelder, Faul, Lang, & Buchner, 2007) indicated that the smallest sample size required (per group) to achieve power of 0.90 to reject the null hypothesis, for a chi-square goodness of fit test, with an alpha cut-off of 0.05 was twenty-seven participants. We thus collected data from more than twenty-seven participants per group to anticipate exclusions. See Supplementary Table 1 for details about age, education, visual experience and Supplementary Table 2 for individual blind participant demographics, cause of blindness and details of any residual visual perception. Data from a pool of sighted participants (18

¹ 50% consistency refers to the percentage of trials in which a participant responded in their dominant perspective, although no instruction was given to adopt any specific perspective. Thus, we considered a participant to be consistent in the perspective they freely adopted in Session 1 if they adopted that perspective in more than 50% of trials. The 50% cut-off was selected in line with previous research using the same task (Arnold et al., 2016, Job et al., 2019).

female, 25 right handed) who completed the same task with full vision (published in Arnold et al., 2016) was also used. A representative sample of thirty participants was pseudo-randomly selected from this dataset (for further details see 2.4. *Data Analysis*). All participants provided written informed consent in accordance with the ethical guidelines outlined by the Declaration of Helsinki (1991).

2.2. Stimuli

The stimuli were identical to those used previously (Arnold et al., 2016). Tactile stimuli were delivered by means of 9 rectangular vibrators (Haptuator Mark II, Tactile Labs, Montreal Canada) arranged in a 3-by-3 array with centre-to-centre spacing of 5cm (see Figure 1.B). The tracing of the letters consisted of a sequence of 8 vibrotactile stimuli mapping the trajectory of vibrations as if the letters were traced beginning from the stem. The vibrator array was placed on the participant’s abdomen symmetrically to their body mid-sagittal line. Participants individually selected the intensity of each vibrator by means of a method of adjustment. The participants wore noise-reducing headphones in order to mask any sounds made by the vibrators.

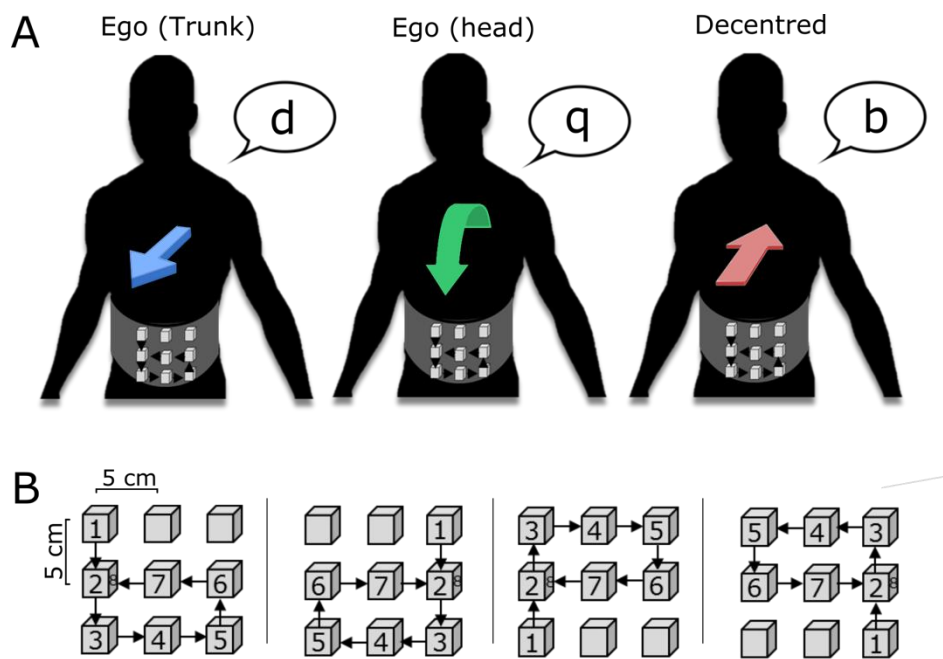


Figure 1. A) Schematic illustration of the Graphesthesia task. Three possible spatial perspectives and their corresponding responses for the letter ‘b’ delivered to participant’s abdomen using a tactile belt. Those adopting an egocentred (trunk) perspective report the mirror reversed letter ‘d’, as if perceived from an internal perspective. Those adopting an egocentred (head) perspective report the 180°-rotated

letter 'q', as if the head was orienting down toward the abdomen. Those adopting a decentred perspective report the letter 'b', as if perceived from an external location. B) Schematic illustration of the 3-by-3 array of rectangular vibrators. Sequences of 8 vibrations present the letters 'b', 'd', 'p' and 'q' on the abdomen (decentred perspective). The duration of each vibration was 250ms, without intervals between each vibration.

2.3. Procedure

The procedure was identical to that previously used (Arnold et al., 2016) with minor amendments to accommodate for the lack of vision. In particular, the early-blind, late-blind and blindfolded sighted participants were all given a 3D wooden letter to explore tactually while the task was explained to them. The sighted participants, the data of which was taken from a previous study (Arnold et al., 2016), were also shown the same 3D wooden letter but were not instructed to explore it tactually (see Supplementary Information 3 for more details). The task consisted of three sessions of a tactile letter recognition task. In Session 1 participants were free to adopt any perspective to recognise the letters. The instructions given were scripted in order to avoid biasing the participant toward any particular perspective (e.g. statements referring to any single perspective were avoided). They were informed that each letter could be recognised in different ways, depending on how they assign the left-right and top-bottom axes. They were instructed to report the letter they perceived as spontaneously as possible and that consequently there were no correct or incorrect responses (see Supplementary Information 4 for the instructions in full). In sessions 2 and 3 they were instructed to adopt a specific perspective: either the same as in Session 1 or a different one. For those who spontaneously adopted an egocentred (either a trunk or head-centred) perspective in Session 1, a decentred perspective was imposed. For those who spontaneously adopted a decentred perspective, the trunk-centred perspective imposed. Half of the participants performed Session 2 with the same perspective as in Session 1 and Session 3 with the different perspective. The other half of participants did the opposite.

Participants gave their responses with their preferred hand by pressing one of four adjacent keys on the keyboard which were associated with the letters b, d, p, and q. Participants placed their four fingers of their right hand above the four keys and were instructed to press the first key for 'b', the second for 'd', the third for 'p' and the fourth for 'q'. Participants had 3000 ms after the end of the last vibration to respond, with a 3000 ms inter-trial interval. Each session was composed of 3 blocks of 16 trials (4 presentations of each letter). At the beginning of Session 1, the participants performed a practice block with one presentation of

each letter. No feedback was given for Session 1 as participants were free to recognise the letters spontaneously. At the beginning of Sessions 2 and 3, the practice block was composed of 3 presentations of each letter. During the practice blocks of Sessions 2 and 3 accuracy feedback was given verbally. This was not the case during test blocks, for which participants were informed of their percentage accuracy and mean response times at the end of each block.

2.4. Data analysis

2.4.1. Proportions of spatial perspectives spontaneously adopted

In order to investigate the effects of vision on the proportions of spatial perspectives spontaneously adopted, proportions of participants adopting trunk-centred, head-centred and decentred perspectives for the groups without vision (early-blind, late-blind and blindfolded-sighted) were compared to the proportions observed in a sighted population. A chi-square goodness of fit test was used to identify if the observed proportions of spatial perspectives (head-centred, trunk-centred and decentred) differed from expected. Expected values were obtained from previous research using the same task in adult populations with full vision ($n=250$ in Arnold et al., 2016; and $n=50$ in Job, Kirsch, Inard, Arnold, & Auvray, 2019). These studies have reliably found that 50% of individuals spontaneously adopt an egocentred (trunk-centred) perspective, 30% an egocentred (head-centred) perspective and 20% a decentred perspective in this task². These values were therefore entered into the model as expected values.

Next, to compare the proportions of spatial perspectives spontaneously adopted between the groups without vision, the proportions were entered into a Pearson chi-square test of independence with a factor of Group (early-blind, late-blind and blindfolded-sighted) and Perspective (head-centred, trunk-centred and decentred). Post-hoc comparisons were made using cellwise residual analysis (García-Pérez & Núñez-Antón, 2003) and correction for multiple comparisons was made using Bonferroni adjustment.

² Note that previous studies included younger samples ($M=25.24$ years (Arnold et al., 2016) and $M=26.91$ years (Job et al., 2019) compared to this study, $M=39.49$ years). However, additional control analyses show that age has no significant effect on the perspective spontaneously adopted in both the dataset of Arnold and colleagues (Arnold et al., 2016) and the present dataset (see Supplementary Information 5. for details). Thus, age does not account for the differences between the observed and expected proportions of natural perspectives.

2.4.2. *Cost of switching perspectives*

To investigate flexibility of perspective taking, switch-cost data from a previously published study (Arnold et al., 2016) were used where the same protocol was run. The data from 30/80 participants who completed the task with vision were analysed, in order to match the sample sizes. Given that the proportions of natural perspectives differed between the sighted participants and those who underwent the same experiment without vision (see Results 3.1 below), the 30 participants (18 female, 25 right-handed) were selected pseudo-randomly, with the proportions of natural perspective constrained to match that of the blind groups (i.e. .27 for trunk-centred, .66 for head-centred and .07 for decentred). The proportions were matched so that any difference in the cost of switching perspectives could not simply be attributed to differences in the proportion of perspectives adopted across the groups. See Supplementary Information 7 for equivalent analyses without the matching procedure. An ANOVA with a within-subjects factor of Switch (before-switch/after-switch) and a between-subjects factor of Group (early-blind, late-blind and sighted) was used on accuracy and reaction times. Post-hoc comparisons were made using Bonferroni adjustment. Where violations of the assumption of equal variances were found, Welch's robust test was used, and post-hoc comparisons were made using Games-Howell method.

For those participants who returned to their natural perspective in Session 3 (half of participants) an ANOVA with a within-subjects factor of Block (S2B3 and S3B1) and a between-subjects factor of Group (Early-blind, Late-blind and Sighted) was run on accuracy and reaction times. This was done to verify an improvement in participants' performance when returning to their natural perspective in Session 3, thus demonstrating that the perspective spontaneously adopted was indeed natural.

3. Results

3.1. Proportions of spatial perspectives adopted

The chi-square goodness of fit test revealed a significant deviation from the expected proportions of each spatial perspective for the early-blind group ($\chi^2(2)=12.90$, $p=.002$), the late-blind group ($\chi^2(2)=30.88$, $p<.001$) and the blindfolded-sighted group ($\chi^2(2)=15.19$, $p=.001$). Thus, all of the groups without vision significantly differed from sighted individuals in the perspectives they spontaneously adopted (see Figure 2A). The head-centred perspective was adopted more by the early-blind group (0.61), the late-blind group (0.75) and the

blindfolded-sighted group (0.50), in comparison to the expected percentage observed in sighted individuals (.30). Less trunk-centred perspectives were observed compared to expected (0.50) for the early-blind group (.32), the late-blind group (0.19) and the blindfolded-sighted group (0.18). Decentred perspectives were adopted less by the early-blind (.07) and the late-blind (.06) compared to the sighted (.20) individuals, however more decentred perspectives were adopted by the blindfolded-sighted group (.32), see Figure 2A.

The Pearson chi square test of independence revealed a significant association between Perspective (trunk-centred, head-centred and decentred) and Group (early-blind, late-blind and blindfolded-sighted; $\chi^2(4)=12.27, p=.015$). Post-hoc cellwise residual analysis indicated that a significantly higher proportion of the decentred perspectives was found in the blindfolded-sighted group ($p=.001$), however no other cell significantly deviated from expected (all p -values $> .05$). Table 1 shows the observed and expected frequencies for each group and perspective with their respective proportions and p -values.

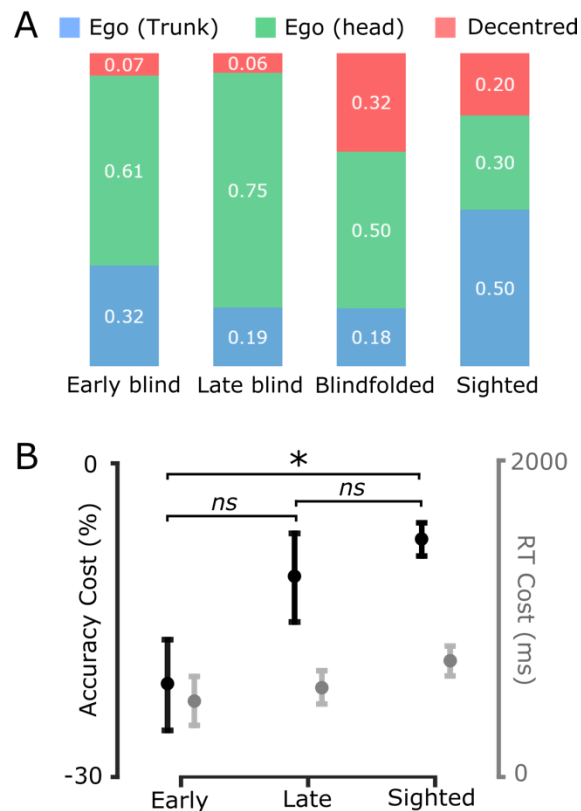


Figure 2. A) Proportions of each perspective spontaneously adopted in the free session (Session 1) for each group. B) Accuracy and reaction time results before and after switching to a different perspective. Performance decreased post-switch (lower accuracy and higher RTs) for all groups, however more so for the Early-blind vs. the Sighted.

Table 1. Results of the Pearson chi-square test of independence for the spatial perspectives adopted by the groups without vision (early-blind, late-blind and blindfolded). Observed frequencies (Freq.) are compared to frequencies expected from the internal characteristics of the dataset (Expected Freq.)

		Spatial Perspective			Total
		Trunk-centred	Head-centred	Decentred	
Blindfolded	Freq.	7	19	12	38
	Expected Freq.	9	23	6	
	Residual (z)	-.8	-1.8	3.3	
	Proportion	.18	.50	.32	
	p-value	.447	.070	.001	
Early-blind	Freq.	9	17	2	28
	Expected Freq.	6	17	5	
	Residual (z)	1.5	-.1	-1.6	
	Proportion	.32	.61	.07	
	p-value	.146	.948	.120	
Late-blind	Freq.	6	24	2	32
	Expected Freq.	7	20	5	
	Residual (z)	-.6	1.9	-1.9	
	Proportion	.19	.75	.06	
	p-value	.541	.051	.060	

3.2. Cost of switching perspective

Accuracy significantly decreased when switching to an unnatural perspective ($M=13.15\%$, $SE=2.10$, $F(1,87)=37.11$, $p<.001$, $\eta_p^2=.301$, CI [8.97 17.32]) and reaction times significantly increased ($M=547\text{ms}$, $SE=73.38$, $F(1,85)=55.60$, $p<.001$, $\eta_p^2=.395$, CI [401.28 693.09]). The groups also significantly differed in their overall accuracy ($F(2,87)=10.97$, $p<.001$, $\eta_p^2=.201$), but not in their reaction times ($F(2,85)=1.94$, $p=.150$, $\eta_p^2=.044$). Post-hoc comparisons revealed significantly higher accuracy for the Sighted group ($M=94.89\%$, $SE=3.18$) compared to the Early-blind ($M=73.99$, $SE=3.29$, $p<.001$, CI [9.73 32.07]) and the Late-blind group ($M=80.86$, $SE=3.08$, $p=.006$, CI [3.24 24.84]). Accuracy did not significantly differ between the Early and Late-blind groups ($M=6.86$, $SE=4.51$, $p=.394$, CI [-4.14 17.86]). A significant interaction between Switch and Group was observed for accuracy ($F(2,87)=3.78$, $p=.027$, $\eta_p^2=.080$), but not for reaction times ($F(2,85)=.90$, $p=.409$, $\eta_p^2=.021$). Post-hoc comparisons revealed a significantly greater accuracy switch-cost for the Early-blind group compared to the Sighted group ($M=13.91$, $SE=4.65$, $t(35.88)=2.99$, $p=.005$, CI [4.47 23.36]). The accuracy switch-cost did not significantly differ between the Late-blind and the Sighted

groups ($M=3.64$, $SE=4.55$, $t(40.35)=.80$, $p=.428$, $CI [-5.56 12.85]$) or between the Early and Late-blind groups ($M=10.27$, $SE=6.08$, $t(58)=1.67$, $p=.097$, $CI [4.47 23.36]$).

Accuracy significantly improved when participants returned to their natural perspective ($M=9.81\%$, $SE=3.02$, $F(1,44)=10.57$, $p=.002$, $\eta_p^2=.194$) and reaction times also significantly decreased ($M=370.78\text{ms}$, $SE=98.72$, $F(1,44)=14.12$, $p=.001$, $\eta_p^2=.243$), confirming that the perspectives spontaneously adopted were indeed natural. In addition, the groups also significantly differed in their overall accuracy ($F(2,44)=4.35$, $p=.019$, $\eta_p^2=.165$), but not in their reaction times ($F(2,44)=0.52$, $p=.569$, $\eta_p^2=.025$). Post-hoc comparisons revealed a higher mean accuracy for the Sighted group ($M=94.42\%$, $SE=4.49$) compared to the Early-blind group ($M=77.93$, $SE=4.19$, $p=.031$, $CI [1.20 31.78]$) and a marginally higher mean accuracy for the Sighted compared to the Late-blind group ($M=79.41$, $SE=4.07$, $p=.051$, $CI [-.07 30.09]$). No significant difference in accuracy was found between the Early and Late-blind groups ($M=1.48$, $SE=5.85$, $p=1.000$, $CI [-13.07 16.03]$). No significant interaction between Block and Group was observed for accuracy ($F(2,44)=0.84$, $p=.439$, $\eta_p^2=.037$), or for reaction times ($F(2,44)=1.23$, $p=.301$, $\eta_p^2=.053$) when returning to the natural perspective.

4. Discussion

This study investigated the role that visual experience plays in shaping spatial perspectives used to interpret tactile information. Early-blind, late-blind, blindfolded-sighted, and sighted participants reported the identity of ambiguous tactile stimuli presented on their abdomen. Firstly, how vision affects the spatial perspective (head-centred, trunk-centred or decentred) that one spontaneously adopts during free recognition was investigated by comparing the proportions of perspectives adopted between each group. Secondly, how visual experience affects the flexibility with which one can change spatial perspective was investigated by comparing switch-costs between groups of early-blind, late-blind and sighted individuals.

During free recognition, those without vision (early-blind, late-blind and blindfolded-sighted) spontaneously adopted more egocentred perspectives compared to sighted participants. Interestingly, the egocentred perspective adopted most by those without vision was the head-centred, rather than the trunk-centred, perspective. This is the first study to show not only that those without vision (even temporarily) adopt less external-decentred spatial perspectives, but that they also adopt more egocentred perspectives specifically anchored to the head. The finding that those with even a temporary lack of vision adopted more head-centred, rather

than more trunk-centred coordinates, was unexpected. However, the head-centred perspective may have been more spontaneously adopted than the trunk-centred one due to these perspectives corresponding to a mental localization of the stimulus either on the body (proximal attribution) or in external space (distal attribution), respectively (see Fig. 1A). Visual deprivation may promote the mental localisation of stimuli onto the body (perspective anchored to the head) rather than mentally projecting stimuli in front of the body (perspective anchored to the trunk). This is in line with findings that closing one's eyes shifts attention to the somatosensory modality (Kawashima, O'Sullivan, & Roland, 1995). An earlier preliminary study (Shimojo, Sasaki, Parsons & Torii, 1989) showed overall similar patterns of egocentred and decentred perspectives adopted by early-blind and sighted individuals. However, the stimuli were manually drawn by an experimenter (rather than automatically by means of a tactile belt used here), which is known to bias responses toward a decentred perspective (i.e. the perspective of the experimenter) (Arnold, Spence & Auvray, 2017). Furthermore, that study neglected to investigate the head-centred perspective, which results in incorrect proportions of decentred versus egocentred perspectives when the stimulated body part is located below the head (Arnold et al., 2017). Future research could systematically vary the stimulated body part, as this could affect which perspective is spontaneously adopted (e.g. for an investigation of spatial perspective-taking for tactile stimuli delivered to the tongue see Richardson, Lloyd-Esenkaya, Petrini, & Proulx, 2020).

When comparing the proportions of perspectives spontaneously adopted by the groups without vision (early-blind, late-blind and blindfolded), a greater proportion of decentred perspectives was found for the blindfolded-sighted group. This suggests that regardless of the onset (i.e. early or late), blindness appears to reduce processing in decentred spatial coordinates. This is in line with previous results showing worse recall for object locations in decentred coordinates for the blind (Coluccia, Mammarella, & Cornoldi, 2009). These inter-individual differences in perspective-taking are of importance not only at the fundamental level, but also for the design of tactile interfaces for the blind (see Arnold, Pesnot-Lerousseau, & Auvray, 2017).

Finally, compared to the sighted group, those with less than three years of visual experience (early-blind) had a greater cost of switching to an unnatural perspective. This supports the view that a lack of early visual experience may limit the simultaneous representation of information across spatial perspectives, in line with recent findings using a spatial memory task (Ruggiero, Ruotolo, & Iachini, 2018). It is noteworthy that the procedure slightly

differed between the groups without vision and the sighted group (i.e. the manual exploration of 3D wooden letters to explain the shapes, see Supplementary Information 3), which could conceivably account for the group differences observed here. However, the procedure was identical for both the early-blind and late-blind groups, thus if procedural differences accounted for the switch costs results, then the late-blind group would also have significantly differed from the sighted group. The small procedural difference is therefore unlikely to account for differences only between the sighted and early-blind groups. The blindfolded sighted group did not complete Sessions 2 and 3 because there was no reason to believe that merely a lack of vision during the task would affect the flexibility of spatial perspective taking, and thus this was not part of our hypotheses. However, the possibility of such an effect cannot be excluded and could be investigated in future studies.

Research is beginning to show that sensory loss or deprivation can have a profound influence on spatial perspective-taking, by altering the perspective adopted to perceive stimuli in an intact modality (Arnold, Sarlegna, Fernandez, & Auvray, 2019; Ferrè, Lopez, & Haggard, 2014). These findings were interpreted as evidence that sensory loss modifies the perceived location of one's self in space. Interestingly, the self is often subjectively located in the head or the trunk, with important inter-individual variability (Alsmith & Longo, 2014). In the present study, we showed that blindness and temporary visual deprivation favour head-centred rather than trunk-centred spatial perspectives. The extent to which a loss of vision affects not only spatial perspective-taking but also the perceived location of the self remains an open research question.

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Author contributions

G. Arnold and M. Auvray developed the study concept and design. Data collection was performed by G. Arnold. Data analysis was performed by G. Arnold, X. Job and L. Kirsch. The manuscript was drafted by X. Job; G. Arnold, L. Kirsch and M. Auvray provided critical revisions. All authors approved the final manuscript for submission.

Declaration of conflicting interests

The authors declare that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Supplementary Information

Supplementary Table 1. Means (*M*) and Standard Deviations (*SD*) of age, onset of blindness and years of education across the groups.

	Early-blind (n=28)		Late-blind (n=32)		Blindfolded (n=38)	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Age (years)	40.11	9.53	40.78	9.76	37.13	13.58
Onset of blindness (years)	.55	.98	17.75	11.86	n/a	n/a
Years of education	14.46	2.50	14.13	2.55	15.79	2.62

A one-way ANOVA with a factor of Group (early-blind, late-blind and sighted-blindfolded) showed no difference between the age of the groups ($F(2,97)=1.03$, $p=.360$).

However, a significant effect of group was found for years of education $F(2,97)=4.14$, $p=.019$. Post hoc pair-wise comparisons (Bonferroni corrected) indicated that the late blind group had significantly less years of education compared to the sighted-blindfolded group ($M=-1.66$, $SE=.62$; $p=.024$, $CI [-3.16 -.16]$). However, the difference between early blind and sighted-blindfolded ($M=1.33$, $SE=.64$; $p=.122$, $CI [-.23 2.88]$) and the difference between early blind and late blind groups ($M=.34$, $SE=.65$; $p=1.000$, $CI [-1.28 1.96]$) were not significant.

2. Table of information about the blind participants

Supplementary Table 2. Characteristics of blind participants

Ppt.	Age	Sex	Handedness	Years of Education	Years of vision	Cause of blindness	Visual Perception
1	23	F	Right	13	0.75	Bilateral retinoblastoma	Diffuse light
2	45	F	Right	16	0	Leber's congenital amaurosis	None
3	40	M	Right	17	2.5	Atrophy to the eyeballs	None
4	35	F	Right	16	0	Leber's congenital amaurosis	Diffuse light
5	28	F	Right	11	1.4	Facial burns	Diffuse light
6	29	M	Ambidextrous	17	0.5	Medical error at birth (forceps)	None
7	32	F	Right	15	0	Unknown virus	None
8	44	F	Right	15	0	Malformation during pregnancy	None
9	36	M	Ambidextrous	17	0.25	Leber's congenital amaurosis	Diffuse light
10	45	F	Right	16	0	Leber's congenital amaurosis	Diffuse light

11	32	F	Right	15	0	Unidentified congenital disease	Diffuse light
12	39	M	Left	12	0	Congenital glaucoma	None
13	42	F	Right	9	0	Burned optic nerves	None
14	52	F	Ambidextrous	12	0	Retinal damage during pregnancy	Diffuse light
15	29	F	Right	12	3	Optic nerves removed (brain tumor)	Diffuse light
16	57	M	Right	14	0	Retinitis Pigmentosa	None
17	42	M	Right	14	0	Congenital glaucoma	None
18	53	M	Right	8	0	Congenital glaucoma	Diffuse light
19	27	M	Right	17	0	Optic nerve damage at birth	Diffuse light
20	31	F	Right	15	0	Congenital glaucoma	Diffuse light
21	50	M	Left	14	2.5	Craneosynostosis	Diffuse light
22	45	F	Right	16	0	Premature birth (Hyperoxia)	None
23	46	M	Right	12	0	Bilateral retinoblastoma	None
24	36	M	Right	16	2.5	Nutritional deficiency	None
25	47	F	Right	17	0	Retinal detachment	None
26	48	F	Right	17	0	Leber's congenital amaurosis	Diffuse light
27	58	M	Right	17	2	Retinitis Pigmentosa	Diffuse light
28	32	F	Right	15	0	Leber's congenital amaurosis	None
29	41	M	Right	15	14	Unknown	None
30	24	M	Ambidextrous	14	11	Bilateral glaucoma	None
31	53	M	Right	12	10	Bilateral glaucoma	None
32	46	F	Right	14	37	Retinitis Pigmentosa	Diffuse light
33	32	F	Left	18	15	Retinal degeneration	None
34	41	M	Right	16	8	Congenital glaucoma	None
35	42	F	Right	15	5	Optic nerve damage	Diffuse light
36	50	M	Right	14	37	Marfan syndrome + glaucoma	None
37	19	M	Right	13	6	Retinal degeneration	Diffuse light
38	49	F	Right	14	23	Congenital retinal lesions	Diffuse light
39	33	F	Right	16	6	Glaucoma + retinal detachment	None
40	45	F	Right	12	20	Behcet's disease	Diffuse light
41	31	F	Right	13	22	Retinitis Pigmentosa	Diffuse light
42	33	M	Right	16	26	Macular degeneration	None
43	50	F	Right	17	39	Retinitis Pigmentosa	Diffuse light
44	44	F	Right	18	15	Optic nerve damage (trauma)	Diffuse light
45	30	F	Right	14	5	Optic nerve damage (brain tumor)	Diffuse light
46	52	M	Right	12	22	Retinal detachment	Diffuse light
47	40	F	Right	11	5	Optic nerve damage (trauma)	None
48	22	M	Right	10	16	Glaucoma + cataracts	Diffuse light
49	45	M	Right	16	27	Retinal damage (trauma)	Diffuse light
50	55	F	Right	14	6.5	Bilateral glaucoma	None
51	47	M	Right	11	14	Congenital glaucoma	None
52	33	M	Left	14	12	Retinitis Pigmentosa	Diffuse light
53	43	M	Right	10	14	Malignant myopia (retinal detachment)	Diffuse light
54	38	M	Right	12	20	Retinitis Pigmentosa	Diffuse light
55	51	M	Right	20	7	Glaucoma	None
56	39	M	Right	9	10	Retinitis Pigmentosa	Diffuse light
57	33	F	Right	17	23	Diabetic retinopathy	Diffuse light

58	37	M	Right	14	4.5	Diabetic retinopathy	None
59	50	M	Left	16	43	Glaucoma	Diffuse light
60	57	F	Right	15	45	Retinitus Pigmentosa	Diffuse light

3. Differences between the procedures used here and in Arnold et al., (2016)

The procedure was identical to that of Arnold et al., (2016) except for the following. For the blind and sighted-blindfolded participants, small wooden letters were used to explain to the participants the shapes that were going to be drawn on their abdomen. Before the first session, the four b, d, p, and q wooden letters were fixed on the table, from left to right in that order. The participants first freely explored the four letters (2D exploration). Then, the experimenter guided participant's index finger of their dominant hand along the letters, with the same trajectory as the vibration sequences (i.e., beginning from the stem). Finally, the experimenter highlighted that the four letters were all made of a stem and a loop and that they were both horizontally and vertically symmetrical. Then, the participants explored the four letters again. The sighted-blindfolded participants were blindfolded before entering the experimental room.

Before Session 2, the experimenter explained to the participants how the letters can be interpreted differently as a function of the adopted perspective (as in Arnold et al., 2016). Following this another wooden letter the same size as the tactile letters drawn on the abdomen was given to the participant to hold and freely manipulate (3D exploration).

4. Instructions given before Session 1 (translated from French to English)

“You may have already realized this, or you may realize it when you start, that because these letters are symmetrical to each other (both horizontally and vertically) there are several possible answers each time a letter is drawn on your abdomen. It all depends on how you think about things. It's done on purpose. In this first part, we don't impose on you how you should interpret them on your abdomen. There are no right and wrong answers per se. Your task is to try to answer as spontaneously as possible, indicating the first letter that comes to mind. You must find the simplest way for you to think about these letters on your abdomen, the one that allows you to answer with as little thought as possible.”

5. Effects of age

A one-way ANOVA with a factor of Perspective (trunk-centred, head-centred and decentred) was conducted on the age of the participants reported in Arnold, Spence and Auvray (2016).

Age did not significantly differ across those who spontaneously adopted a trunk-centred, head-centred or decentred perspective ($F(2,75)=.81, p=.449$).

Similarly, in the data reported in the present study, age did not significantly differ across those who spontaneously adopted a trunk-centred, head-centred or decentred perspective ($F(2,95)=.63, p=.536$).

6. Effects of congenital blindness

Selecting only the congenitally blind ($n=19$) and excluding those who lost their vision before three years of age ($n=9$) did not change the pattern of effects observed. For the proportions of natural perspectives adopted, the congenitally blind group significantly differed from expected (the chi-square goodness of fit test revealed a significant deviation from the expected proportions of each spatial perspective for the congenitally blind group ($\chi^2(2)=17.33, p<.001$). A significantly greater accuracy switch-cost for the Congenitally blind group compared to the Sighted group was found ($M=14.08, SE=5.90, t(21.31)=2.44, p=.024, CI [2.07 26.11]$) and no significant difference between the congenitally blind and late blind groups was observed ($M=10.44, SE=6.96, t(49)=1.50, p=.140, CI [-3.68 24.56]$). Therefore, combining congenitally blind and those with up to three years of visual experience into one 'early blind' group has little consequence for the results.

7. Selection of data from Arnold et al., (2016)

If a random sample of 30 participants is selected from the sighted population, but the proportions of natural perspectives are not matched to that of the blind groups, then the same pattern of results is observed, i.e. a significantly greater accuracy switch-cost for the Early-blind group compared to the Sighted group ($M=14.12, SE=5.5, t(56)=2.57, p=.012, CI [3.07 25.17]$), but not between the Late-blind group and the Sighted group ($M=3.85, SE=5.46, t(60)=0.71, p=.484, CI [-7.09 14.79]$). Similarly, when using the entire dataset of sighted participants (i.e. no longer randomly selecting 30 participants matched to the blind groups), the pattern of results was also the same, i.e. a significantly greater accuracy switch-cost for the Early-blind group compared to the Sighted group ($M=14.39, SE=4.47, t(30.39)=3.21, p=.003, CI [5.26 23.52]$), but not between the Late-blind group and the Sighted group ($M=4.12, SE=4.37, t(35.08)=0.94, p=.353, CI [-4.75 13.00]$). Note that where a violation of the assumption of homogeneity of variance was found (Levene's test for Equality of Variances was significant), the values were adjusted accordingly.