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This is a copy of the accepted author manuscript of an article subsequently published in *Perception* 45 (3) 281-299 0301-0066, Sage.

https://dx.doi.org/10.1177/0301006615607157

Allocentric spatial performance higher in early-blind and sighted adults than in retinopathy-of-prematurity adults.

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Running title: Spatial frameworks in the blind & sighted

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Acknowledgements: Thanks to Barbara Tversky and Holly Taylor and our participants. Thanks also to Morton Heller for his invaluable advice on an earlier draft of the manuscript.

The question as to whether people totally blind since infancy process allocentric or ‘external’ spatial information like the sighted has caused considerable debate within the literature. Due to the extreme rarity of the population, researchers have often included individuals with Retinopathy of Prematurity (RoP – over oxygenation at birth) within the sample. However, RoP is inextricably confounded with prematurity per se. Prematurity, without visual disability, has been associated with spatial processing difficulties. In this experiment, blindfolded sighted and two groups of functionally totally blind participants heard text descriptions from a survey (allocentric) or route (egocentric) perspective. One blind group lost their sight due to retinopathy of prematurity (RoP – over oxygenation at birth) and a second group before 24 months of age. The accuracy of participants’ mental representations derived from the text descriptions were assessed via questions and maps. The RoP participants had lower scores than the sighted and early blind, who performed similarly. In other words, it was not visual impairment alone that resulted in impaired allocentric spatial performance in this task, but visual impairment together with RoP. This finding may help explain the contradictions within the existing literature on the role of vision in allocentric spatial processing.

Key words: mental representation, blind, allocentric, spatial, egocentric, visually impaired

Explaining the origins and nature of cognitive spatial representation remains a problem in perceptual literature. One of the key points for investigation has been the role of vision in spatial mental representation, with researchers comparing performance of blind and sighted individuals. Researchers looking at the role of vision in spatial mental representation have been particularly interested in two important versions of such representations - allocentric and egocentric. Allocentric space is also known as external, exocentric or extrinsic layout. It is a set of locations with respect to external objects or general frames of reference such as North, South, East or West. In contrast, egocentric encoding is body-centric or intrinsic. It is a set of directions and distances from the observer's vantage point. It uses proprioceptive, mid-line and other posture cues. It is about what is left, right, above and below. Allocentric information can be encoded independently from egocentric representations (Mou, McNamara, Valiquette & Rump; 2004; O'Keefe & Nadel; 1978; Eardley & Van Velzen, 2011). Individuals without sight are capable of employing both allocentric and egocentric spatial mechanisms. However, contradictory findings in the literature have left researchers arguing over whether or not visual information is necessary for adaptive allocentric spatial processing.

Spatial information can be derived from non-visual sensory information. Indeed Lessard, Pare, Lepore and Lessonde (1998) report that, compared to the sighted, individuals born totally blind are better able to develop a 3D map of space from auditory stimuli, and are more accurate at localising sounds presented monaurally. The congenitally blind are found to be better than the sighted at localising sound in peripheral areas (Röder, Teder-Salejarvi, Sterr, Rosler, Hillyard & Neville, 1999), and have superior tactile spatial acuity

(Van Boven, Hamilton, Kauffman, Keenan & Pascual-Leone, 2000; Forester, Eardley & Eimer, 2007). Their improved performance may be due to better stimulus encoding (Rokem & Ahissar, 2009).

Nevertheless, information about 3D spatial location of multiple objects in different depth planes is superior in vision. For example, height information is often given optically by the horizon ratio (Sedgwick, 1973). Indeed, it has been argued that vision is necessary for adaptive spatial processing and that it plays a particular role in allocentric representations of space (Thinus-Blanc & Gaunet, 1997). Despite enhanced performance on spatial perceptual tasks, research comparing spatial abilities in people who are blind, sighted and blindfolded-sighted individuals has produced mixed results, particularly in relation to allocentric spatial processing. Individuals born without sight have performed less well than sighted participants on navigation (e.g. Reiser, Hill, Talor, Bradfield & Rosen, 1992; Reiser, Lockman & Pick, 1980), spatial inference (e.g. Cleaves & Royal, 1979; Coluccia, Mammarella & Cornoldi, 2009; Ruggiero, Ruotolo & Iachini, 2009) and mental imagery tasks (e.g. Cornoldi, Cortesi & Preti, 1991; Vecchi, Monticelli & Cornoldi, 1995; Vecchi, 1998). Some researchers suggest that vision is necessary for efficient external location (Thinus-Blanc & Gaunet, 1997; Ungar, 2000; Vecchi, 1998), and automatic evocation of allocentric spatial reference (Röder, Kusmierek, Spence, & Schicke, 2007).

Undermining this argument, several studies have reported sighted and congenitally-blind equivalence on navigation (Loomis et al., 1993), spatial inference

(Lewis, Collis, Nock, Burns & Twisleton, 2004) and spatial imagery (Eardley & Pring, 2007). Others identified superior performance in the congenitally blind in allocentric spatial tasks (Ittyerah, Gaunet & Rossetti, 2007; Tinti, Adenzato, Tamietto & Cornoldi, 2006). Indeed, research has suggested that allocentric representations of space may be automatically evoked for both the sighted and early blind individuals, although early blind individuals may not be so bound to use them (Eardley & Van Velzen, 2011).

Some researchers have attempted to explain the differences in performance by suggesting that early blind individuals can adopt either allocentric or egocentric perspectives but prefer the latter (Gaunet & Rossetti, 2006; Millar, 1988; Noordzij, Zuidhoek & Postma, 2006; Postma, Zuidhoek, Noordzij & Kappers, 2007). However, this explanation would not account for instances of superior performance by the blind (e.g. Ittyerah et al., 2007; Tinti et al., 2006). More helpful is the suggestion that mobility training and independent-living experience improves spatial performance (Millar, 1994; Loomis et al., 1993). Extensive mobility training/independent living experience may be particularly true for allocentric spatial understanding (Fiehler, Reuschel & Rösler, 2009). However, it is not the only possible explanation.

The conflicting results in previous studies examining the role of vision in spatial processing may be the result of a confound. A common cause of total blindness from infancy is retinopathy of prematurity (RoP) – previously known as retrolental fibroplasia. Most common in the 1950’s and 60’s, RoP affects babies who were born very premature, and who were over oxygenated in the first few days of life. A side effect of this is detachment of the retina, which causes blindness. Prematurity without blindness has been associated with impaired spatial skills (Curtis, Lindeke, Georgieff, & Nelson, 2002; Vicari, Caravale, Carlesimo, Casadei, & Allemand, 2004). In line with this, research has suggested that individuals with RoP may have impaired spatial processing (Stuart, 1995), relative to other early blind people. A great deal of the research on blindness includes a proportion of RoP participants. If a group of blind volunteers in a research study includes many with RoP, this could result in misleading conclusions about the impact of visual impairment on spatial processing. A simple solution is to compare performance on a spatial task of people who are blind as a result of RoP both with those who are early blind not as a result of RoP and people who are normally sighted. This enables the researcher to identify whether or not a lack of early vision, per se, causes spatial difficulties.

In this experiment, spatial layouts were verbally described to blind and sighted participants (Taylor & Tversky, 1992a, 1992b, 1996). Allocentric awareness of a spatial layout (mental maps - Tolman, 1948) allows inferences about short-cuts, detours and efficient navigation avoiding pitfalls (Tversky, 2000). This is equally the case for spatial layouts understood from direct perceptual experience or verbal description (Avraamides, Loomis, Klatzky & Golledge, 2004; Loomis, Klatzky, Avraamides, Linna, & Golledge, 2007; Mellet, et al., 2002; Noordzij & Postma, 2005).

Taylor and Tversky (1992a) prepared two descriptions for each of four spatial environments. One used extrinsic-reference language (e.g. north, south). The other described routes, using egocentric language (e.g. left, right, in front). Four descriptions were read by sighted participants, two extrinsic and two as routes. It was left to the participants to determine how they would anchor cardinal directions. After each text, participants responded to true or false statements, which were verbatim Quotes from the descriptions, Paraphrases or statements requiring inferences. The verbatim Quotes and the Paraphrases all described spatial relations within the texts that the participants had heard. As such, these could be answered purely based on verbal memory. However, all of the spatial relations within the inference statements were novel. For example, if participants heard “A is to the left of B, and C is below B”, then an inference would be necessary to correctly respond to the question: “Is A northwest of C?” As such, correct responses to inference statements demonstrated an allocentric mental representation of the spatial environment. Participants also drew maps of the environments. Testing sighted participants, Taylor & Tversky (1992a) found no differences in response time or accuracy between description conditions. Although accuracy was greater for the verbatim Quotes and Paraphrases, irrespective of the text perspective, participants responded above chance to the inference statements. As such, they concluded that allocentric and egocentric understanding of space was generated regardless of text perspective. However, this may not be the case for people with no sight from infancy if either vision does pay a crucial role in adaptive allocentric spatial processing (e.g. Thinus-blanc & Gaunet, 1997; Röder et al., 2007), or people who are early blind have a preference for egocentric spatial mental representation (e.g. Noordzij et al., 2006; Postma et al., 2007).

This research used the Taylor and Tversky paradigm with individuals with RoP, an early blind group, as well as blindfolded sighted participants. Participants responded to questions about the spaces described, and created physical maps of the spaces (see Ungar, Blades & Spencer, 1996; Edwards, Ungar & Blades, 1998; Ungar, Espinosa Bayal, Blades, Ochaita & Spencer, 1998; Blades, Lippa, Golledge, Jacobson & Kitchin, 2002). The key question was how early-blind and RoP participants would perform, compared to the sighted, on verbatim Quotes and inference statements for allocentric 'survey' and egocentric 'route' texts. Based on the findings that people without sight do automatically generate allocentric spatial frameworks, and given the evidence demonstrating equivalent allocentric processing in people without sight, and the suggested spatial deficits in RoP individuals, we expected that:

1. The Retinopathy of Prematurity would perform least well on allocentric inference statements and map generation.
2. The early blind group would perform equivalently to the sighted on the allocentric tasks.

<u>**Method**</u>

Participants

Data was collected from a total of 23 participants without sight and 20 participants with sight. Both groups of participants were recruited via responses to advertisements in magazines for people with a visual impairment and via word of mouth. Of the participants without sight, the data from four participants were rejected because of: a failure to understand the task (early blind); a technical problem resulting in data loss (early blind); a failure to carry out the full requirements of the task (early blind); and finally a rejection due to a ‘yes’ response bias (early blind). This resulted in a group of 19 participants without sight, 10 of whom were male and 9 female. The 19 participants without sight were functionally totally blind – with either no vision at all or some diffuse light but no form perception. A verbal IQ test (WAIS-RNI - Kaplan, Fein, Morris, & Delis, 1991) was carried out to ensure that participants all had cognitive function within the normal or above normal range. Given that IQ tests are not normed for use with Visually Impaired participants, only a gross level of accuracy was assumed (Atkins, Cobb, Keil, Home & Wilkins, 2012). All participants had a verbal IQ score > 100. There was no difference in IQ across the three groups (RoP group, early blind and sighted) of participants ($F_{2, 36}$=3.01**,** p=N/S). The demographics of participants without sight can be found in Table 1. The blind participants fell into two groups. The first was an RoP group (RoP, n=8). The median age was 55.0 (range 25-60). The second, the early blind group (n=11), included the participants who had lost their sight before 24 months old (median age 57.0, range 51-61). All participants were independent, active individuals (by self-report).

Of the 20 sighted participants (median age: 56.5, range 28-69), 10 were female and 10 were male. A non-parametric Kruskal Wallis one-way ANOVA examining age indicated that there were no significant differences across the participant groups ($\chi^2(2)$=3,38**,** p=N/S).

Table 1: Demographics of participants without sight.

	Sex	Age	Age at loss of sight	Residual sight	Medical Diagnosis
Retinopathy of Prematurity					
1	M	54	Early postnatal	None	Retinopathy of Prematurity
2	F	56	Early Postnatal	None	Retinopathy of Prematurity
3	F	25	Early Postnatal	Light/shade	Retinopathy of Prematurity
4	F	25	Early Postnatal	Light/shade	Retinopathy of Prematurity
5	F	56	Early Postnatal	None	Retinopathy of Prematurity
6	M	56	Early Postnatal	None	Retinopathy of Prematurity
7	F	52	Early Postnatal	Light/shade	Retinopathy of Prematurity
8	F	54	Early Postnatal	Light/shade	Retinopathy of Prematurity
Early Blind					
1	M	52	Birth	None	Mother had Rubella
2	M	61	2 years (deterioration before)	None	Retinal Blastoma
3	F	57	18 months	None	Unspecified viral infection
4	M	61	18 Months	Light/shade	Trauma to eyes – bomb explosion
5	F	61	5 months 1st eye; 2nd 18 months	None	Retinal Blastoma
6	M	60	Birth	Light/shade	Lebers Amerosis
7	M	51	Birth	None	Absence of optic nerve
8	M	51	13 months	None	Retinal Blastoma

			(deterioration from 6 wks)		
9	M	60	2 years (deterioration before)	None	Retinal Blastoma
10	M	57	13 months (deterioration before)	None	Retinal Blastoma
11	F	53	Birth	Light/shade	Mother had Rubella

The research was approved by the Laval University Ethics committee and carried out according to their guidelines, and in accordance with the BPS guidelines.

Materials

Four environment layouts, based on those devised by Taylor and Tversky (1992a), were used in this study. Each environment had 11 or 12 key features. The environment layouts used were a small town ('Etna' – see Appendices 1-3), a conference centre ('conference'), a zoo ('zoo') and a holiday resort region ('resort'). For each environment layout, Taylor and Tversky (1992a) prepared two texts describing the environment and containing both locative (spatial) and nonlocative information. One text described the environment from an allocentric or 'survey' perspective (see Appendix 1). These texts made use of the cardinal points north, south, east and west. The other text described the environment from an egocentric or ‘route’ perspective (see appendix 2). These texts centred on the individuals’ locations using directions such as left or right.

Changes were made to the Taylor and Tversky (1992a) texts for use in the UK (e.g. replacing ‘intersection’ with ‘crossroads’ or ‘store’ with ‘grocery shop’) and with participants without sight (e.g. replacing “on your left, you will see the school” with “on your left, will be the school”).

For each of the four environments, a set of 40 statements was prepared, to which the participant had to respond ‘true’ or ‘false’. The original 36 statements used by Taylor and Tversky (1992a) were supplemented with 4 additional statements. These 40 statements contained 11 different types of statement. Irrespective of the perspective from which the texts were heard, all participants responded to the same 40 statements. For example, if a participant heard the ‘Etna’ environment from the survey perspective, he or she then had to respond to statements which were verbatim copies of the survey text that had just been heard, and to statements which were verbatim from the route text but which the participant had not heard (see appendix 3).

All texts were narrated via a computer programme, which also recorded the reaction time and accuracy data, running on a portable laptop computer. The voice was a computer generated program called ‘Mike’ from AT& T’s Natural voice™ software. The speed at which the voice talked was fixed. Participants listened through headphones.

A QWERTY laptop keyboard was used to register responses. The ‘c’ key was covered in a white label upon which was printed a black ‘F’. This was covered by an ‘F’ Brailed in clear plastic, through which the printed ‘F’ was clearly visible. The ‘m’ key was covered by a white label upon which was printed a black ‘T’. This was in turn covered by a ‘T’ Brailed in clear plastic.

A blindfold was used for sighted participants, whilst they were listening to the texts and responding to the statements.

Participants were also required to generate tactile maps. For this purpose, participants were provided with a range of foam pieces and a metal board. The foam pieces consisted of a series of lines, squares, circles and rectangles of differing sizes, which were cut out of 10mm thick bucklite foam, with a magnetic strip on one side and a piece of Velcro on the opposite side. For each key feature, a cardboard backed label was made, upon which the item name could be read in both script and Braille. The labels had Velcro on the underside so that they could be attached to the appropriate foam piece by the participant.

Design

For the verbal descriptions task, a mixed design was used, with "Visual Status" (choices of RoP, Early blind, Sighted) as a between-subjects variable, and "Text Perspective" (choices between Route and Survey), "Statement Accord" (choice between Yes and No) with respect to the text perspective, and "Statement Type" (choice between Quotes, Paraphrases, and Inferences) as within-subject variables.

Participants heard all four environments from *either* a route or a survey perspective. The blind participants each heard two route and two allocentric descriptions. The order of environment presentation was counterbalanced across participants, with each environment presented the same number of times in each perspective participants, across participants. This counterbalanced order was matched for sighted participants. Regardless of the text perspective, the same sets of 40 statements were judged to be true or false by all participants. False statements were included to check for a potential 'yes' responding bias, and were not considered in the main analyses. The remaining 36 statements consisted of locative and nonlocative statements. The locative statements were presented from two perspectives, one which was in accord with the description that had been heard, and one which was not. There were three types of locative statements – verbatim Quotes, Paraphrases and inference statements. The Paraphrases consisted of directions or spatial relationships explicitly described within the text, but worded differently. The inference statements described spatial relationships between items which were implied but not explicitly stated within the descriptions.

The proportion of correct statements across survey and route texts was calculated for each participant. This proportion represented one dependent variable. A second dependent variable was the time taken to respond, in milliseconds, to each statement. Reaction Time was measured from the moment the statement began to be narrated to the participant (via the computer programme). This allowed for responses made before the narration of the statement had finished. Due to the differences in length of some of the statements, reaction time (in seconds) per word variable was created. The reaction time (in seconds) variable was divided by the number of words in the statement. The two dependent variables were analysed separately.

The map task also used a mixed design with "Visual Status" (RoP/Early blind/Sighted) as a between-subjects variable, and "Text Perspective" (Route/Survey) and “Statement Accord" (Yes/No) to the text Perspective as within-subject variables. Each participant listened to four environments. They were asked to generate maps for the 2nd and 3rd of the environments they listened to (environments were counterbalanced across participants). For all participants one map was based on a route description and one on a survey description, with the order being counterbalanced across participants. When maps were required, after hearing the text and responding to the statements, participants were asked to generate a map of that environment. Sighted participants removed their blindfold for this task so as not to be impaired by their lack of facility with tactile information. When the maps were completed, a digital photo was taken, which was used as the basis for scoring the maps. The dependent variable for the map task was based on the number of relations within the verbal descriptions, both explicit and implicit, which were correctly represented on the map. For an element to be scored correct, both verbal labelling and spatial position had to be correct. Both exact and more general relations were scored. For example, if the ticket booth (in the zoo text) was both south and west of the entrance (as was described in the text), then two points were scored. However, a point was also given for the ticket booth simply being ‘next’ to the entrance. This enabled the awarding of partial credit if, for example, the participant had correctly positioned the ticket booth close to the entrance, even if it had been incorrectly placed just to the north and east of the entrance.

Procedure

All participants were tested in a quiet room in their own homes. Participants were seated at a table, with the laptop computer. They were asked to listen to four descriptions of different environments, each about 400 words long. They could listen to the texts up to four times or for a maximum of 10 minutes. Instructions told participants that once they felt they would be able to describe the environment to someone else, they should start to respond to statements about the text. Participants were asked to place their left index finger on the key marked ‘F’ for false and their right index finger on the key marked ‘T’ for true.

Following the brief verbal introduction, sighted participants were asked to wear the blindfold, and all participants were asked to wear the headphones. Participants were informed that they could control the speed at which the sentences were presented. Individual sentences could not be repeated. They were instructed to respond to the statements as quickly but as accurately as possible. The computer instructions finished with a practice session in which participants had to listen to a brief text and respond true or false to three statements about that text.

For the descriptions for which maps were created, when the final statement had been recorded, participants were instructed to remove their headphones. In order that they were not impaired by a lack of familiarity in the tactile modality, sighted participants also removed their blindfold. All participants were then asked to try and construct a map of the practice environment that they had just heard. The metal board was placed in front of participants, with a selection of foam shapes next to them. They were to select a foam piece, and verbalize its label. The experimenter then handed them the appropriate written/brailed label, which was then to be attached to the foam piece to identify what it represented. The participant then placed the piece on the appropriate position on the metal board.

On completion of the practice map making session, and after participants' questions had been answered, the experimental session began. Individuals listened to text one, and then responded to the associated statements, followed by text 2, and the associated statements. Having heard the text and statements for environment 2, participants were asked to generate a tactile map of that environment. The third text was listened to and the statements responded to, and a second tactile map was created. Participants then listened to the fourth and final text and responded to the associated statements. They were debriefed, and the experimental session ended.

During the course of a different experiment, carried out on a different day, verbal IQ data was collected for all participants involved in this study using the Wechsler Adult Intelligence Scale Revised Neuropsychological Instrument (WAIS-RNI).

Results

Part 1: Proportion of correct responses

Responses to the nonlocative statements were at ceiling for all groups. Performance on these statements was not considered further.

The descriptive statistics for the accuracy scores suggested that whilst performance was similar across Visual Status groups for both Quotes and Paraphrases, overall performance was lower for Inference questions, with RoP individuals performing particularly poorly (See Table 2).

Table 2: Mean (and Standard deviations) proportion of correct responses for Quotes, Paraphrases and Inference questions for Visual Status groups (collapsed for text perspective). Inference accuracy combines Inferences statements from the same and different perspectives.

		Quotes	Paraphrases	Inference
Visual Status	**Retinopathy of Prematurity (RoP)**	.83 *(.06)*	.74 *(.06)*	.55 *(.08)*
	Early blind	.80 *(.07)*	.78 *(.11)*	.73 *(.12)*
	Sighted	.79 *(.06)*	.79 *(.09)*	.69 *(.11)*

A 2 (Perspective) x 2 (Accord) x 3 (Statement) x 3 (Visual Status) ANOVA examined the relationship between the Perspective of the text (route/survey), the accord between the Statement perspective and the text Perspective (yes/no), and the type of statement posed in relation to the texts heard (verbatim Quotes/Paraphrases/Inferences) for the Visual Status groups (RoP/early blind/sighted). The dependent variable was the mean proportion of correct responses. Where sphericity could not be assumed, the Greenhouse Geisser correction was used. Result that did not reach significance (p=N/S) were not reported.

The ANOVA revealed significant main effects of Accord ($F_{1, 36}$ =118.33, p<.001) and Statement Type ($F_{1.72, 61.81}$ =32.17, p<.001). Overall, all participants found the questions in accord with the text Perspective type easier than those in a different perspective.

Further, Bonferonni-corrected pairwise comparisons of the main effect of Statement Type confirmed that participants found the inference statements harder than either the Quotes (mean difference: .126, p<.001) or the Paraphrases (mean difference: .102, p<.001). In other words, when participants had to go beyond verbal memory (Quotes/Paraphrases) to respond (e.g. inference statements and all statements not in accord with the text perspective), they found it harder.

There was a significant two-way interaction between Perspective x Accord (F1, 36 =5.86, p=.021). The repeated measures t-tests indicated that, when the statements were in accord with the text perspective, participants performed better on the survey descriptions than they did on the route descriptions (*t* (38)=3.94, p<.001). In other words, overall survey statements were easier than route statements, and this was irrespective of Visual Status.

There were also interactions between Accord x Statement ($F_{1.92,\ 69.02}$ =39.77, p<.001) and Statement x Visual Status ($F_{3.43,\ 61.81}$ =5.22, p=.002), but these were superseded by a three way interaction between Accord x Statement x Visual Status ($F_{3.84,\ 69.08}$ =3.37, p=.015). Consequently, only the three way interaction is discussed. When Accord is 'no', basically all the statements are in a different perspective and are consequently inference statements. To break down this three-way interaction, for each Statement Type (Quotes, Paraphrases, Inferences), we examined whether there was a difference in how visual status groups responded for each level of Accord (Visual Status x Accord). For the Quotes, there was a main effect of Accord only ($F_{1,\ 36}$ =134.90, p<.001), with all participants performing much better when the text perspective was in accord. This is because it is only when there was an accord that statements were indeed Quotes (rather than Inferences). For the Paraphrases, the same main effect of Accord was identified ($F_{1, 36}$ =123.39, p<.001), such that all participants performed much better at Paraphrases in the same text perspective (the true paraphrases), than in the different text perspective. However, there was also an interaction between Accord and Visual Status ($F_{1, 36}$ =4.69, p=.016). This revealed that although there was no difference in the proportion correct where the Paraphrases were in accord with the text perspective, when the Paraphrases were not in accord (e.g. inference statements), the sighted group did marginally better overall than the RoP group (Mean difference: .125, p=.042).

Finally, for the Inference statements, there was no main effect for Accord (all questions required an inference, irrespective of the text perspective, so this is not surprising), and no interaction between Accord and Visual Status. However, there was a main effect of Visual Status ($F_{2, 36}$ =7.93, p=.001). Bonferoni-corrected pairwise comparisons confirmed that the RoP group performed significantly worse than either the early-blind (Mean difference: -.184, p=.002) or the sighted (Mean difference: -.158, p=.005). There was no difference in the accuracy of the early blind and sighted (Mean difference: .036, p=N/S). In other words, the RoP group were worse at the inference statements than the early blind and sighted groups.

A final analysis was carried out to explore whether or not participants were performing above chance. With 50% equal to chance, Table 2 shows that the sighted and early blind perform well above chance for all question types, but the RoP group are close to 50% for Inferences. The difference between the RoP group and others was significant (on one-sample *t*-tests on responses to the inference, the RoP participants were at chance (t (7) = 1.67, p=N/S). However, for the both the verbatim and paraphrased statements for the RoP group, and for all Statement Types for both the early blind and sighted groups, responses rates were significantly better than chance (all t>6.5, p<.001).

Part 2: Response time

The RoP group were significantly less accurate than the sighted and early blind, who performed equivalently. Response times (RT) (calculated per word in the statements) were analysed to check for a speed/accuracy trade off. Only correct responses were analysed.

Table 3: Mean (and Standard deviations) of response time (in seconds) per word (for correct responses only) for Quotes, Paraphrases and Inference questions for Visual Status groups (collapsed for text perspective). The means for inference statements combined inference statements from the same and different perspectives.

		Quotes	**Paraphrases**	**Inference**
Visual	**Retinopathy of Prematurity**	.44 *(.06)*	.50 *(.11)*	.59 *(.14)*

Status	**(RoP)**			
	Early blind	.43 *(.08)*	.46 *(.08)*	.63 *(.12)*
	Sighted	.43 *(.05)*	.45 *(.06)*	.60 *(.10)*

As for accuracy, a 2 (Perspective) x 2 (Accord) x 3 (Statement) x 3 (Visual Status) ANOVA was run. There was a main effect of Accord ($F_{1, 36}$=26.89, p<.001), a main effect of Statement ($F_{1.62, 58.29}$=69.4, p<.001), an interaction between Perspective and Accord ($F_{1, 36}$=32.44, p<.001), an interaction between Accord and Statement ($F_{1.66, 58.29}$=8.35, p=.001), and an interaction between Perspective, Accord, Statement and Visual Status ($F_{3.86, 69.53}$=2.75, p=.036). No other main effects or interactions were significant.

Paired sampled tests explored the interaction, demonstrating that for survey texts, the speed of response was the same whether the statements were given from a survey or route perspective (*t* (39)=0.469, p=N/S). This was not the case for route texts. Here, statements from the same (route) perspective were responded to significantly faster than statements from the survey perspective (*t* (39)=9.914, p<.001). Further, when the route statements were presented after a route text, participants responded faster than when survey statements were heard after a survey text (*t* (39)=4.579, p<.001). However, of key interest, participants found it easier to answer route statements following a survey text than they did the reverse (*t* (39)=4.868, p<.001). For the four-way interaction we were only interested to see if there were differences between Visual Status groups. Consequently, the interaction was assessed as a function of the survey and route perspectives individually. For both, there was a significant interaction between Accord, Statement Type and Visual Status (Survey: $F_{(3.297, 61.996)}$ = 2.71, p=.047; Route: $F_{(3.588, 66.373)}$ = 2.71, p=.043). However, when this was broken down further, to look at Statement Type for each level of Accord for the survey and route perspective respectively, there were no results p<.05. No effects of Visual Status were found when the interaction was broken down by Statement Type, nor by Accord. In other words, there are no significant differences across Visual Status groups in reaction times.

Part 3: Maps

The number of relations correctly represented on the map for each respective environment description was translated into a percentage of the total possible correct relationships (see Table 3). Standard deviations were high, irrespective of text Perspective, suggesting strong individual differences across all Visual Status groups. A 2 (Perspective) x 3 (Visual Status) mixed design ANOVA found only a main effect of Visual Status ($F_{2, 36}$ =6.2, p=.005).

Table 4: Mean and standard deviations for the proportion of correct elements placed on maps for Visual Status groups for each text Perspective

	Text Perspective	
	Survey	**Route**

Visual Status	**Retinopathy of Prematurity (RoP)**	34.04 *(31.51)*	37.68 *(17.86)*
	Early blind	65.06 *(26.22)*	58.34 *(23.12)*
	Sighted	68.92 *(26.78)*	61.26 *(18.73)*

Posthoc Bonferroni-corrected comparisons indicated that RoP participants performed significantly worse than both early blind individuals (mean difference: -25.84, p=.028) and Sighted individuals (Mean difference: -29.23, p=.004). However, there was no difference in performance between early blind and sighted individuals (Mean difference: 3.39, p=N/S).

Discussion

The RoP group responded least accurately to the allocentric inference statements. Their responses were just at chance level. There were no differences in the accuracy levels of the early blind and sighted group on the inference statements, and both groups' response accuracy were significantly above chance levels. There was also no difference across the three groups on Quotes and Paraphrases. Taken together, this confirms that although all groups are equally able to meet the task demands when required to make use of the verbal information when thinking about the texts, the RoP group had a specific difficulty on the allocentric spatial questions. Furthermore, early blind individuals perform equivalently on allocentric spatial tasks to the sighted.

Contrary to previous findings, blind participants were not slower than sighted participants on this allocentric spatial task (for a review see Thinus-Blanc & Gaunet, 1997). Thus, the accuracy of the early blind and sighted group (relative to the RoP individuals) was not the result of a speed/accuracy trade off. The RoP group also had difficulty generating maps, irrespective of the perspective of the text (route or survey).

Taken together, these results support the assertion that early sight loss alone is not the cause of deficits in spatial processing. The results suggest that other factors, for example issues related to RoP, may have a role to play. Given that some of the participants in this research have had some early visual experience, performance of the four congenitally blind participants in the early-blind group, whose sight loss did not result from RoP, was compared to that of the RoP group. Evidently, with such small numbers results from inference tests can only be tentative. Nevertheless, it is worth noting that an ANOVA comparing the RoP group and the 4 congenitally blind participants showed that there was a significant difference in performance on the inference statements between the two groups ($p=.049$). Indeed, one sample t-tests confirmed that whilst the RoP participants' responses on the inference statements were not significantly above chance ($p>.5$), the congenitally blind but not premature participants were ($p=.014$). These tentative results support the assertion that the differences between early blind and RoP participants cannot be explained purely by early visual experience.

Due to the extreme rarity of the early blind and RoP participants, we were not able to match on sex for these groups. Consequently, there was a higher proportion of male participants in the early blind group, and a higher proportion of female participants in the RoP group. Research on sex difference in spatial tasks have shown that whilst there are differences on some tasks (mental rotation), there are no differences on spatial visualisation tasks (Voyer, Voyer, & Bryden, 1995). Furthermore, women may be better at spatial memory than men (e.g. McBurney, Gaulin, Devineni, & Adams, 1997). Given that this experiment required both spatial visualisation and spatial memory, any sex differences should only have served to advantage the RoP group, relative to the other groups.

It is possible that it is the complexity of the task rather than spatial ability per se that is producing the difficulty for the RoP group. The task is a demanding one. Nevertheless, all participants had verbal IQ scores greater than 100. There was also no difference between IQ scores across the three participant groups. Most crucially, RoP individuals did not have any difficulty, relative to other participant groups, with the verbatim Quotes or paraphrased information. Difficulties were observed uniquely on tasks requiring allocentric spatial processing.

This research strongly suggests that a lack of vision from infancy, per se, is not sufficient to produce suboptimal allocentric spatial processing. Rather, other factors not specifically related to loss of vision, for example RoP, may play a role. Previous research has suggested that the fact that RoP individuals have a particular difficulty with allocentric information is in line with evidence of spatial deficit in premature but not visually impaired children (Curtis et al., 2002; Vicari et al., 2004) and with previous suggestions in the literature of a specific spatial impairment for RoP children (Stuart, 1995). However, further research is needed to examine the specific relationship between prematurity, RoP and spatial processing. This is particularly true given the observation that one participant RoP participant produced 100% accurate maps for the survey perspective. The next highest RoP performer only placed 50% of items accurately. Knauff and May (2006) also identified the RoP group as poor performers in spatial reasoning tasks, with the exception of one individual with excellent performance. There were no obvious external factors which might have resulted in particularly enhanced spatial skill – for example her job was not especially reliant on spatial understanding. She was one of the few participants who used a cane, rather than a guide dog, as a mobility aid. An examination of the neural basis of spatial mental representation and its development in premature individuals with and without RoP, and with and without this spatial deficit, might help to explain the mechanisms underlying mental representations of space in both the blind and sighted. Further exploration could also uncover whether or not this deficit extends to other tasks requiring allocentric spatial processes, for example taking another's point of view.

These results demonstrate not only that RoP perform less well than early blind and sighted individuals in allocentric spatial tasks, but also that there is no significant difference between performance levels of the early blind and sighted. This is in line with previous research which has shown that lack of vision per se does not result in quantitative differences in the formation of a spatial mental representation (e.g. Loomis et al., 1993; Klatzky, Golledge, Loomis, Cicinelli & Pellegrino, 1995; Landau, Spelke & Gleitman, 1984). As such, it would seem likely that individuals with spatial deficits resulting from RoP and not a lack of vision per se would have negatively skewed performance by 'blind' groups, and this might account for some of the poorer performance by 'blind' participants groups. Nevertheless, it is important to note that although there may be functional equivalence in allocentric spatial understanding derived from visual or nonvisual information, in at least some instances, vision (or the lack of) still has an impact on the way allocentric spatial information is processed (Eardley & Van Velzen, 2011).

In sum, evidence from verbal responses and map generation found that an early blind group and a blindfolded-sighted group performed similarly, but that an RoP blind group performed at a chance level on some allocentric spatial tasks. As such, it is not a lack of vision from infancy per se which results in sub-optimum spatial processing. Rather, difficulties in spatial processing may result in other root causes, for example, RoP. Consequently, whilst this research supports the claim that functional equivalent allocentric spatial processing may be possible without visual experience, future research is needed to clarify the exact relationship between prematurity, blindness and spatial processing.

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Appendix 1 – Verbal description of 'Etna' – Survey text

One of the largest town fairs and pumpkin festivals in the United States is held each year in the town of Etna. Etna is a typical small town in New England. The layout of the town has not changed much since it was founded in the 1700s. Etna and its surrounding areas are bordered by four major landmarks: the White Mountains, the White River, the River Highway and Mountain Road. The northern border is made up of the White Mountain Range. Running north-south along the western boarder of this region is the White River. The southern border is made up of the River Highway. Along the eastern border, connecting the River Highway to the mountains, is Mountain Road. Most of Etna lies west of Mountain Road, just north of its crossroads with the River Highway. Etna is built around four streets that surround the Town Park. On the eastern edge of the park, there is a white Bandstand. The Bandstand is used to house the town orchestra during afternoon concerts. Along the eastern edge of the Town Park runs Mountain Road. The other three streets in Etna are each only a block long. Along the southern border of the park runs Maple Street. Maple Street is lined with large maple trees. These maples, when they come alive with colour in the autumn, are an attraction for many tourists. Across the street from the park, on separate sides, lie three of the town's main buildings – the Town Hall, the Shop, and the School. Across the street from the east side of the park is the Town Hall. The Town Hall is the oldest structure in the town and one of the buildings around which the town was built. Across the street from the north side of the park is the Grocery shop. People often gather at the shop to find out the latest news. Across the street from the west side of the park is the School. The little red, one-roomed school building is the original school built when the town was founded. At the northwest corner of River Highway and Mountain Road is the Petrol Station. One of the employees from the Petrol Station sits in front of the station office and waves to all the cars that drive past.

Appendix 2 – Verbal description of 'Etna' – Route text

One of the largest town fairs and pumpkin festivals in the United States is held each year in the town of Etna. Etna is a typical small town in New England. The layout of the town has not changed much since it was founded in the 1700s. To reach Etna, drive along the River Highway to where the highway crosses the White River. Continuing on the River Highway, for another half a mile past the river, you come to, on your left, Mountain Road. You have reached the town of Etna. As you turn left onto Mountain Road from the River Highway, you will pass on your immediate left, the Petrol Station. One of the employees from the Petrol Station sits in front of the station office and waves to all the cars that drive past. Straight ahead, the road disappears into the distant White Mountains. You drive on Mountain Road a block past the petrol station, and come to, on your left, Maple Street. Turning left onto Maple Street, you see that the street is lined with large maple trees. These maples, when they come alive with colour in the autumn, are an attraction for many tourists. After turning left onto Maple Street from Mountain Road, you see, on your right, the Town Park – a central feature of Etna. You travel a block on Maple Street and you are forced to make a right turn. On your left, about a half a block after you turn off of Maple Street, is the School. The little red, one-roomed school building is the original school built when the town was founded. Continuing along this street for another half a block, you are again forced to make a right turn. You turn and drive half a block where you see, on your left, the Grocery shop. People often gather at the shop to find out the latest town news. This road continues for another half a block where it dead-ends into Mountain Road. After you make a right turn onto Mountain

Road, you drive about a half a block to where you see, on your left, the Town Hall. The Town Hall is the oldest structure in the town and one of the buildings around which the town was built. From your position with the Town Hall on your left, you see, on your right, a white Bandstand near the edge of the park. The Bandstand is used to house the town orchestra during afternoon concerts. You return to where Mountain Road dead-ends into the River Highway. You turn left from Mountain Road and leave the town of Etna by taking the River Highway.

Appendix 3 – Verbal description of 'Etna' – Statements (same set for both survey & route descriptions)

Survey perspective

Verbatim:

1) The northern border is made up of the White Mountain Range.
2) Along the eastern edge of the Town Park runs Mountain Road.
3) On the eastern edge of the Town Park, there is a white Bandstand.
4) At the northwest corner of River Highway and Mountain Road is the Petrol Station.

Paraphrased:

1) The White River runs north-south along the western border of this region.
2) Mountain Road connects the River Highway to the mountains along the eastern border.
3) Maple Street runs along the southern border of the park.
4) The Town Hall is across the street from the east side of the park.

Inference:

1) The closest building to the White River is the School.
2) The Petrol Station is east of the river and south of Maple Street.
3) Directly across the Mountain Road from the Bandstand is the Town Hall.

4) The School is on a road that runs east-west.

5) On the west side of Mountain Road is the Town Hall.

6) Directly across the park from the School is the Petrol Station.

False:

1) Across the street from the east side of the park is the school.

2) The grocery shop is across the street from the south side of the park.

Route perspective:

Verbatim:

1) As you turn left onto Mountain Road from River Highway, you see, on your immediate left, the Petrol Station.

2) You drive on Mountain Road a block past the Petrol Station, and come to, on your left, Maple Street.

3) After turning left onto Maple Street from Mountain Road, you see, on your right, the Town Park - a central feature of Etna.

4) From your position with the Town Hall on your left, you see, on your right, a white Bandstand near the edge of the park.

Paraphrased:

1) Drive east along the River Highway to where the highway crosses the White River to reach Etna.

2) You are forced to make a right turn after you travel a block on Maple Street.
3) You leave the town of Etna by taking the River Highway after turning left from Mountain Road.
4) The School is on your left, about a half a block after you turn off of Maple Street.

Inference:

1) From your position with the Town Hall on your left, the White Mountains are behind you.
2) Driving toward Mountain Road on Maple Street, the School is behind you.
3) Driving from the Town Hall to the Petrol Station, you pass Maple Street on your right.
4) Driving toward the White Mountains on Mountain Road, the Petrol Station and the Town Hall will both be on your right.
5) Coming from the White Mountains on Mountain Road, you turn left to reach the Grocery Shop.
6) Driving toward Mountain Road from the Shop, you see, on your left, the Bandstand.

False:

1) Continuing on the River Highway, for another half a mile past the river, you come to, on your right, mountain Road.
2) The layout of the town has not changed much since it was founded in the 1800s.

Nonlocative:

Verbatim:

1) Etna is a typical small town in New England.
2) The Town Hall is the oldest structure in the town and one of the buildings around which the town was built.
3) One of the largest town fairs and pumpkin festivals in the United States is held each year in the town of Etna.
4) People often gather at the Shop to find out the latest town news.

Paraphrased:

1) When they come alive with colour in the autumn, the maples are an attraction for many tourists.
2) Built when the town was founded, the school is in the original little red one-roomed school building.
3) Waving to all the cars that drive past the front of the Petrol Station is one of the station employees.
4) The town orchestra uses the Bandstand for their afternoon concerts.