



Spatial navigation by congenitally blind individuals

Victor R. Schinazi,^{1†*} Tyler Thrash^{1†} and Daniel-Robert Chebat²

Spatial navigation in the absence of vision has been investigated from a variety of perspectives and disciplines. These different approaches have progressed our understanding of spatial knowledge acquisition by blind individuals, including their abilities, strategies, and corresponding mental representations. In this review, we propose a framework for investigating differences in spatial knowledge acquisition by blind and sighted people consisting of three longitudinal models (i.e., convergent, cumulative, and persistent). Recent advances in neuroscience and technological devices have provided novel insights into the different neural mechanisms underlying spatial navigation by blind and sighted people and the potential for functional reorganization. Despite these advances, there is still a lack of consensus regarding the extent to which locomotion and wayfinding depend on amodal spatial representations. This challenge largely stems from methodological limitations such as heterogeneity in the blind population and terminological ambiguity related to the concept of cognitive maps. Coupled with an over-reliance on potential technological solutions, the field has diffused into theoretical and applied branches that do not always communicate. Here, we review research on navigation by congenitally blind individuals with an emphasis on behavioral and neuroscientific evidence, as well as the potential of technological assistance. Throughout the article, we emphasize the need to disentangle strategy choice and performance when discussing the navigation abilities of the blind population. © 2015 The Authors. *WIREs Cognitive Science* published by Wiley Periodicals, Inc.

How to cite this article:
WIREs Cogn Sci 2016, 7:37–58. doi: 10.1002/wcs.1375

INTRODUCTION

Blind individuals are faced with the challenge of finding their way through built environments that can be difficult to interpret, disorienting, and even intimidating.^{1,2} Research on visual impairment

and blindness has approached this challenge by attempting to gain an understanding of the cognitive processes underlying navigation without vision and developing assistive technologies for obstacle avoidance and route selection. Despite the impressive number of technological advances (for reviews, see Refs 3–5), these devices are not often used by the blind population.⁶ At the same time, basic research in visual impairment has somewhat stagnated because of a failure to incorporate modern frameworks and recent findings from the field of spatial cognition. For example, traditional frameworks regarding the microgenesis of spatial knowledge⁷ have resulted in inconsistent interpretations of survey knowledge (often termed ‘cognitive map’). This confusion has led to apparently contradictory results that have

*These authors contributed equally to this study.

†Correspondence to: victor.schinazi@gess.ethz.ch

¹Department of Humanities, Social, and Political Sciences, ETH Zürich, Zürich, Switzerland

²Department of Behavioral Sciences, Ariel University, Ariel, Israel

Conflict of interest: The authors have declared no conflicts of interest for this article.

This paper is dedicated to Roger Schinazi.



propagated through the field and, consequently, a lack of clarity regarding the navigation abilities of blind people.

We approach the topic from the perspective that blind and sighted people may have similar potential (i.e., abilities) for spatial learning that can support navigation. Our position is that, in order to investigate the abilities of blind individuals, researchers should study the relationship between navigation strategies (i.e., the implementation of particular action sequences^{8,9}) and navigation performance (i.e., the extent to which a person is successful with respect to a particular navigation task) rather than approaching either factor independently.¹⁰ Previous research that has studied both strategies and performance has typically constrained blind and sighted participants to adopt *similar* strategies. For example, this occurs when sighted participants are asked to wear blindfolds or when blind participants are asked to complete visually guided tasks (e.g., pointing judgments¹¹). In such cases, a difference in performance is inconclusive with respect to abilities alone because the strategy adopted by both blind and sighted people invariably disadvantages one of the groups. These results are also inconclusive when researchers are unable to detect a difference in performance. Indeed, a nonsignificant difference does not necessarily provide evidence for the absence of an effect. In contrast, allowing participants to adopt *different* strategies would provide insight into the abilities of blind and sighted people. Here, similar performances would indicate similar abilities, and different performances would suggest different abilities (see Figure 1).

In order to provide a comprehensive review on navigation and blindness, we limit ourselves to research on congenitally blind individuals. Previous research often separates the congenitally blind people from the adventitiously blind, blindfolded sighted, and sighted people. Comparisons across these groups

are appropriate but difficult to implement because of lack of agreement regarding the distinction between congenitally and adventitiously blind individuals in terms of acuity, age of onset, and the presence or absence of additional disabilities.^{12–15} In addition, blind groups are often at an advantage when compared to blindfolded sighted groups given their previous reliance on other perceptual modalities. Moreover, comparisons between blind and sighted groups can be problematic if the task inherently favors the visual modality. We will also focus our discussion on meso- and macroscale spaces (i.e., spaces that are larger than the observer and navigable¹⁶), but we will include empirical examples that use microscale spaces in order to infer navigation behavior.

This review is organized into six sections. First, we present behavioral research in human spatial navigation. Here, we discuss the concepts of locomotion and wayfinding, different frames of reference (e.g., egocentric or allocentric), and the affordances provided by different scales of space (e.g., micro, meso, or macro). Second, we discuss discrete and continuous frameworks for the acquisition of spatial knowledge. Third, we contrast different theories regarding the spatial abilities of blind people (i.e., difference, deficiency, and inefficiency¹⁷) as they relate to three possible models for the acquisition of spatial knowledge (i.e., convergent, cumulative, and persistent). Fourth, we discuss multimodal processing (i.e., obtained via various modalities) and amodal representations (i.e., independent of a specific modality¹⁸) such as what is often termed the ‘cognitive map.’ Fifth, we review the neural correlates of navigation by the blind population as they relate to functional reorganization in brain regions specifically associated with navigation. Sixth, we consider the future of research in navigation by blind people including a review of technological advances and heterogeneity in the blind population. At the end of this review, we intend to provide a framework for the interpretation of prior work and the facilitation of future work.

		Strategies	
		Similar	Different
Performance	Similar	Inconclusive	Indicative of similar abilities
	Different	Inconclusive	Indicative of different abilities

FIGURE 1 | Four possible outcomes of studying the interaction between spatial strategies and performances in spatial tasks. The two left cells lead to inconclusive or uninterpretable results with respect to the abilities of the blind and sighted. Future research should focus on the outcomes in the two right cells.

HUMAN SPATIAL NAVIGATION

Everyday, blind individuals navigate indoor and outdoor environments that favor the visual sense. In order to reach a destination, they must plan and execute a series of decisions through these environments. Montello¹⁹ distinguished between wayfinding and locomotion components of spatial decision-making. This distinction corresponds to the terms ‘orientation’ and ‘mobility’ that are commonly used in the

visual impairment literature.²⁰ Locomotion entails immediate responses to environmental features, such as avoiding a fire hydrant or stepping over a curb. These immediate responses are invariably egocentric because environmental information is acquired with reference to the observer's body.²¹ In contrast, wayfinding involves reasoning about immediate²² and remote²³ environments and can employ transient (i.e., short-term) and enduring (i.e., long-term) mental representations.²⁴ During wayfinding, people may also adopt reference frames other than those directly experienced (i.e., allocentric).

Reference Frames and Scales of Space

In wayfinding, egocentric and allocentric reference frames always involve at least one observer, two environmental features, and the spatial relations among them.²⁵ Unlike egocentric reference frames, allocentric reference frames are primarily comprised of object-to-object relations and/or an abstract coordinate system.²⁶ Various types of allocentric reference frames include environmental,²⁵ intrinsic,²⁷ and absolute.²⁸ For the remainder of this study, we will limit ourselves to the distinction between egocentric and allocentric reference frames (for a review, see Klatzky²⁹). There is a tendency to associate blindness with egocentrism,³⁰ especially at larger scales,³¹ but researchers have yet to disentangle whether or not egocentrism in the blind has resulted from aspects of experimental design.¹⁰ For comparisons of blind and sighted individuals, more studies are needed in order to directly compare two types of task and/or performance criteria, one that favors egocentrism and one that favors allocentrism.

Both egocentric and allocentric references frames can be used to represent spaces of different scales. While several frameworks have been proposed,^{22,32} we will use the typology described by Schinazi¹⁶ specifically developed for the classification of experiments with blind and visually impaired individuals. This typology distinguishes between micro- (i.e., manipulatory space that does not require full-body locomotion; see Box 1), meso- (i.e., space that is larger than the observer but can be apprehended from one viewpoint), and macroscales (i.e., space that is larger than the observer but must be apprehended from multiple viewpoints). Previous research has suggested particular associations between the scale of the environment and the adopted frame of reference (for a recent review, see Ref 33), but the adoption of different reference frames may vary with respect to individual and task-related factors (for a review, see Ref 34). Similarly,

BOX 1

WHY CONSIDER THE MICROSCALE?

Many experiments in the visual impairment and navigation literature involve either learning or testing in a microscale space. In some cases, participants are asked to learn a microscale environment from which macroscale behaviors can be inferred.^{36–43} In other cases, participants are asked to learn a macroscale space and transfer this knowledge to a microscale task.^{44,45} There are particular challenges and opportunities associated with each of these approaches.

On the one hand, small-scale experiments^{46,47} (e.g., table-top tasks, tasks in fMRI) restrict participants' locomotion and limit proprioceptive feedback.⁴⁸ In addition, these tasks cannot always dissociate egocentric and allocentric reference frames.³³ Given that navigation at the macroscale requires the coordination of multiple reference frames,^{49,50} these behavioral and neural mechanisms may only be partly represented by studies at the smaller scales³³.

On the other hand, microscale investigations provide a new level of explanation for macroscale behavior using neuroscientific evidence. For example, activation of the occipital lobe during tactile tasks have revealed similarities in the neural processes of blind people doing a tactile task and sighted people doing the same task visually.^{51–54} Although only a subset of these mechanisms can be studied at the microscale,³³ greater experimental control is possible. Indeed, the systematic variation afforded by virtual reality may allow researchers to decompose different stages of navigation at the macroscale. Together, these considerations suggest that learning and testing at the microscale is necessary for navigation research with blind people, but researchers should be cautious when interpreting their results.

scale of space influences choice of navigation strategy.³⁵

Spatial Knowledge Acquisition

At the macroscale, researchers have proposed two frameworks for describing the acquisition of spatial knowledge. The discrete (also known as 'dominant'⁵⁵) framework posits that spatial knowledge is acquired via three, qualitatively distinct stages⁷ (for

an alternative discrete framework, see Ref 56). During the first ‘landmark’ stage, people begin to learn salient features of the environment that can be used for establishing a frame of reference. During the second ‘route’ stage, landmarks become connected via routes that progress from topological to Euclidean formats. These routes allow for the construction of ‘mini-maps’ that are locally, but not globally, coherent.⁵⁷ In the last ‘survey’ stage, people integrate these mini-maps using an objective frame of reference. This global representation is sometimes referred to as a ‘cognitive map’.⁵⁸ Survey knowledge is often considered to be Euclidean in the sense that people can draw inferences regarding the straight-line distance between two points. Along with Golledge⁵⁹ and Shemyakin,⁶⁰ Siegel and White’s⁷ framework was influenced by Piaget and Inhelder’s⁶¹ stage theory of cognitive development.

The alternative ‘continuous’ framework⁵⁵ differs from the discrete framework in at least two ways. First, the strict separation of landmark, route, and survey stages is criticized because people are capable of acquiring different types of spatial information in parallel.^{62–64} Indeed, Schinazi and Epstein⁶⁴ found that, at decision points, landmarks and route information (i.e., direction of travel) were encoded simultaneously. Similarly, Ishikawa and Montello⁶⁵ found large individual differences with respect to the timing of survey knowledge acquisition. Second, Euclidean spatial knowledge is formed earlier in spatial learning than the discrete framework would suggest.^{65,66} These findings support theories of Bayesian integration⁶⁷ and adaptive combination⁶⁸ of different sources of spatial information (e.g., place learning, response learning, cue learning, and dead reckoning). These theories posit that the reliability of spatial cues in the environment help determine the extent to which the corresponding information is acquired.

SPATIAL LEARNING BY BLIND PEOPLE

Similarly, the Convergent Active Processing in Interrelated Networks (CAPIN) theory has described the relative weighting of spatial information obtained through different perceptual modalities.^{69,70} In this case, the weighting is determined by the reliability of the cues provided by each perceptual modality (e.g., the precision of the information specifying an object’s location). Developed from studies with blind and sighted children, this model posits that, in the absence of vision, other modalities receive greater

weight than they otherwise would have. Redundancy in the information received through the different specialized modalities allows individuals to compensate for lack of vision. During wayfinding, some of the information provided by vision, audition, and proprioception is redundant. Compared to the other modalities, vision provides relatively precise information regarding the location of specific features for allocentric encoding. As such, sighted individuals may attribute more weight to vision than to the other modalities. When sighted individuals are blindfolded, these weights will remain the same. Consequently, blindfolded sighted people may underperform relative to blind people, even for tasks that require allocentric encoding.⁷¹ Blind individuals may be similarly capable of allocentric coding via audition and proprioception, but these modalities by themselves are, for the most part, insufficient. The effectiveness of auditory information is limited because not all meaningful features emit sounds, and the effectiveness of proprioceptive information may be limited because of physical barriers. However, the combination of audition and proprioception may facilitate the formation of an allocentric reference frame but at a different time scale (e.g., at the level of eye movements vs at the level of head rotations or walking).

Assuming redundancy in the spatial information provided by different modalities, the CAPIN theory would predict the amount of spatial knowledge acquired by blind and sighted individuals to eventually converge with experience. As such, the pattern predicted by the CAPIN theory represents one of three probable models (inspired by Chen⁷²) for the progression of spatial knowledge acquisition by blind and sighted individuals (see Figure 2). These models represent extensions of the difference, deficiency, and inefficiency theories proposed by Fletcher¹⁷ that characterizes the history of research on the spatial abilities of blind people. Note that these models assume that vision provides sighted individuals with an initial advantage relative to blind individuals, but there have been a few cases in which the blind outperformed the sighted.^{73,74} In addition, different models may apply to different spatial tasks. For a review of differences in memory and inferential tasks, see Ref 75, and for a review of methods in spatial cognition and blindness, see Ref 76.

Convergent Model

Specifically, the difference/convergent model suggests that blind individuals begin at a disadvantage relative to sighted individuals but that this disparity decreases with experience until reaching similar levels of

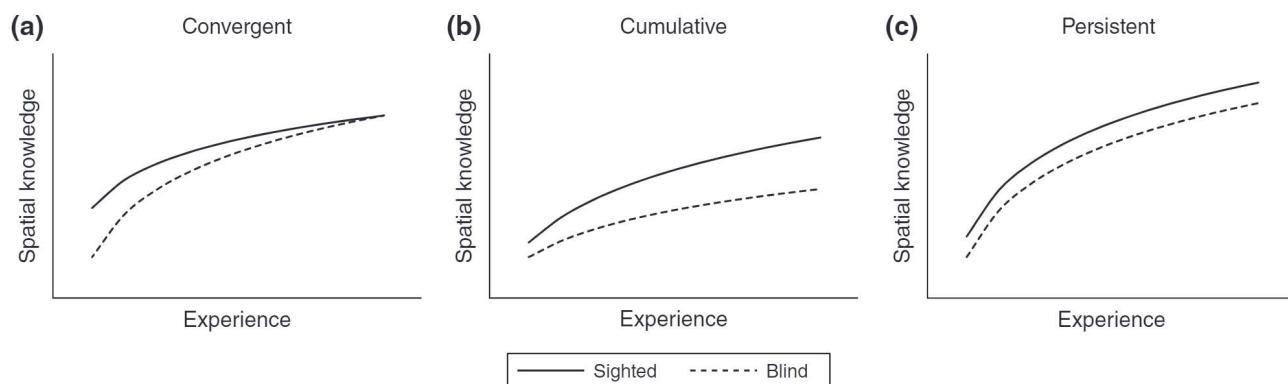


FIGURE 2 | Three models of differences in spatial knowledge acquisition between blind and sighted individuals. On the x-axis is the amount of experience with a particular environment or task. On the y-axis is the extent of spatial knowledge acquisition. Because of the lack of vision, blind individuals start at a disadvantage in each of these models. (a) Convergent model: the difference between blind and sighted individuals decreases over time until reaching a similar level of spatial knowledge. (b) Cumulative model: the difference between blind and sighted individuals increases with experience. (c) Persistent model: blind and sighted individuals continue to acquire spatial knowledge with experience, but differences in spatial knowledge remain constant.

performance. Here, experience may refer to exposure to a particular environment, the repeated performance of a particular task, or the general development of spatial ability with age. This model is supported by several lines of research on tactile discrimination,⁷⁷ tactile matching,⁷⁸ assembly,⁷³ rotation tasks,⁷³ and distance estimation^{73,79} at the microscale. Hollins and Kelley⁸⁰ also found that blind and sighted participants performed similarly in a spatial memory task (i.e., direction estimation) once blind participants were able to touch the task surface.⁸⁰ At the mesoscale, blind and sighted participants performed similarly at triangle completion tasks^{81–83} and walking novel paths among objects in a room.^{84,85} However, Millar¹⁰ and Liben⁸⁶ note that the latter study does not necessarily provide evidence for a Euclidean representation given the curvature in the walked paths and possible auditory cues. In addition, Corazzini and colleagues⁸⁷ found that blind participants exhibited larger learning effects than blindfolded sighted participants in the egocentric condition of an auditory version of a Morris water maze task. However, these results are difficult to interpret because performance in egocentric and allocentric conditions differed on the first trial before learning could have occurred. At the macroscale, research has shown that, although blind participants tend to plan routes in more detail (compared to sighted participants⁸⁸), the accuracy with which models of environments were reconstructed was similar for blind and sighted groups.^{88,89} Indeed, a recent study found that congenitally blind participants outperformed blindfolded sighted participants in terms of shortcircuiting, direction estimates, distance

estimates, and sketch mapping after walking two routes.⁷¹

Cumulative Model

The deficiency/cumulative model suggests that vision is critical for the development of spatial representation and that the progression of spatial knowledge acquisition is slower for blind people relative to sighted people. At its extreme, this model holds that, in the absence of vision, individuals are incapable of forming spatial representations.⁹⁰ According to a relatively moderate interpretation of this model, blind people may be able to acquire spatial knowledge, but the gap between blind and sighted individuals increases with experience. There is little evidence to support this view. For example, Cleaves and Royal⁹¹ found that, for both memory and inferential tasks at the microscale, the disparity in performance between blind and sighted individuals increased with task complexity (i.e., finger mazes) and, for late blind individuals, the time since participants lost their vision. Similarly, at the meso- and macroscales, a longitudinal study found that blind children became less capable at estimating the straight-line directions of different locations in their homes and neighborhoods. This disparity between blind and sighted children increased with the size of the environment under consideration.⁹²

Persistent Model

In the inefficiency/persistent model, the absence of vision results in an initial disadvantage that remains

constant with experience because auditory and proprioceptive cues are less effective for spatial knowledge acquisition than vision. Although spatial knowledge can be acquired by blind people (significantly above chance performance), this knowledge may be less precise and/or less accurate compared to the knowledge of sighted people. Worchsel⁹³ provided initial support for this theory using tasks that involves the reproduction and mental matching of geometric forms at the microscale and is often cited as evidence for inefficiency theory because the tasks favored the visual modality. However, upon careful examination, the results are more in line with the cumulative model given the superior performance of sighted participants and the significant relationship between age of onset and accuracy on spatial tasks.⁹³ It should also be noted that most of the evidence for this theory is based on differences in performance at one particular point in time but is assumed to be the same across time. Consequently, this approach cannot distinguish between the three aforementioned longitudinal models. As a result, the number of studies supporting this theory may be overestimated. At the microscale, the sighted consistently outperformed the blind in a haptic version of the triangle completion task,⁹⁴ mental scanning,⁹⁵ incidental cued-recall test,⁹⁵ perspective-taking,⁹⁶ mental rotation,^{97–99} distance estimation,⁷⁴ direction estimation,¹⁰⁰ and change detection⁷⁵ after locomotion.¹⁰¹ At the mesoscale, the performance of blind participants (relative to sighted participants) is sometimes lower for inferential tasks than memory tasks.^{17,102} However, Rieser and colleagues¹⁰³ found that vision during locomotion can facilitate the completion of particular memory tasks when compared to an inferential task. Similarly, blind participants performed worse than sighted participants in Euclidean and/or functional (i.e., route) distance estimation,^{104,105} direction estimation,¹⁰⁶ and a variety of other spatial tasks (e.g., short-cutting, model construction¹⁰⁷). For the most part, these patterns in performance are also present at the macroscale. Here, blind participants exhibited difficulties in terms of inferential direction tasks,¹⁰⁸ direction estimation from memory,¹⁰⁹ distance estimation,¹¹⁰ model construction,^{44,111} and sketch maps.⁴⁵

Interestingly, there is less support for the persistent model than the convergent or cumulative models in the developmental literature (for a review, see Refs 14,112). Several researchers have reported a pattern that resembles the cumulative model for Piagetian reasoning,¹¹³ projective relations,¹¹⁴ perspective-taking,¹¹⁵ and gross motor skills.^{116–118} According to these studies, vision plays a critical role

in the early stages of development,¹¹⁹ but Millar¹⁰ warns that lags in the Piagetian stages of development may indicate deficiencies in the discrete framework rather than deficiencies in the blind individuals' abilities. Others have suggested that the natural course of development may eliminate performance gaps in terms of sensorimotor understanding and exploration of the environment.¹²⁰ Similarly, early interventions can reduce the gap in Piagetian reasoning.¹²¹ Here, research indicates a convergent pattern as children's spatial thinking becomes more abstract.¹²⁰

SPATIAL PROCESSING AND REPRESENTATION BY BLIND PEOPLE

The spatial representations underlying navigation performance can be abstracted from different perceptual modalities.^{122–124} These modalities vary with respect to the amount of information that can be acquired simultaneously and sequentially.¹²⁵ Previous research has suggested that vision allows for simultaneous perception, whereas audition¹²⁶ and haptics¹²⁷ usually allow for sequential perception. Disadvantages of the blind during navigation have been attributed to this distinction between vision and the other modalities.¹¹² Indeed, a blind person with a cane can typically anticipate only one meter of spatial information per cane movement. However, the extent to which the information acquired by any modality is sequential or simultaneous depends on the spatial and temporal scales under consideration. As such, all of the perceptual modalities are sequential and simultaneous to some extent. Visual information, for example is distributed along time as well as space. The eyes tend to fixate one object at a time as they survey a scene,¹²⁸ and larger scenes require the integration of visual information over a longer period of time. The advantage of vision is thus the speed with which the eyes can move compared to head or body movements. While sensory substitution devices (SSDs) have improved the spatial and temporal resolution of available spatial information (e.g., the EyeCane¹²⁹), this information still needs to be abstracted into an interpretable form (e.g., using artificial intelligence preprocessing⁶).

Multimodal Processing and Amodal Representations

Amodality posits that spatial representations can be abstracted from the perceptual modality through

which the information was originally acquired.^{18,130} Thus far, there are two types of evidence for this proposition. First, several researchers have attributed similarities in the performance of blind and sighted individuals (i.e., convergence) to amodal spatial representations.⁷⁹ Similar performance has been found for mental rotation tasks^{97–99} (but see Klatzky⁷³), mental scanning tasks,^{74,95} incidental cued-recall tasks,⁹⁵ Euclidean and functional distance estimation for regular street networks,⁷⁹ and triangle completion tasks.⁸³ Second, some researchers have investigated the functional equivalence of spatial information acquired through different perceptual modalities (for a review, see Refs 18,130). Here, functional equivalence refers to similarities in performance resulting from information gained through two or more perceptual modalities (or language^{131,132}). These studies have found functional equivalence of vision and language in direction and distance judgments,¹³³ vision and haptics in a spatial updating task,¹³⁴ audition and language in a walk-to-target task,¹³¹ and vision and audition in a spatial working memory task.¹³⁵ In addition, to confirm or disconfirm the primary role of vision, some of these experiments have used blind participants in addition to the blindfolded sighted or sighted participants.^{131,134}

Despite these efforts, amodality remains an open issue in the literature because of the difficulty in disentangling representation and process using behavioral data.¹³⁶ Any hypothesis regarding the format of a representation underlying behavior must assume (either implicitly or explicitly) particular processes and vice versa.¹³⁶ As such, the CAPIN model assumes that amodal representations underlie spatial behavior in order to support the hypothesis that spatial information can be acquired through multiple modalities.⁶⁹ However, multimodal processing may also be paired with modality-specific representations to form an alternative theory. Similarly, amodal representation may be paired with modality-specific processing.^{18,130} In order to provide evidence for or against amodal representation, we propose an approach using Bayesian models of integration.⁶⁷ Here, for a navigation task, one would systematically vary the reliability of location cues from two different modalities (e.g., vision and audition) and the distance between the indicated locations. These two sets of parameters can be used in order to calculate the optimal localization response (according to the Bayesian model) from trial to trial. On the one hand, significant deviations from this optimal response would indicate evidence against amodality. Such deviations may result from either a failure to

integrate the two cues or a disparity between the objective cues and the perceived cues. This disparity may be used in order to match cues from different modalities (e.g., vision and audition) in terms of perceived information content (e.g., distal access). At the same time, this possibility can be eliminated by also obtaining responses to the two cues individually (as recommended by Cheng et al.⁶⁷). On the other hand, the extent to which the Bayesian model can predict localization responses would indicate evidence towards amodality.

Cognitive Maps

The amodal representations underlying navigation are often referred to as ‘cognitive maps.’ Psychologist Edward Tolman¹³⁷ coined the term ‘cognitive map’ in 1948 in order to describe the neural mapping of stimuli to responses. Although he investigated the spatial behavior of ‘hungry’ rats in a variety of mazes, he intended the term to be used more broadly.¹³⁸ This is evident in his discussion of such topics as motivation during development and race relations. Over two decades later, O’Keefe and Burgess¹³⁹ referred to Tolman in order to define their discovery of ‘a cognitive, or spatial, map of [a rat’s] environment’ (p. 171). In the introduction to *The Hippocampus as a Cognitive Map*, O’Keefe and Burgess¹⁴⁰ later revised this reference to Tolman by acknowledging that the original definition of cognitive map was too vague for their purposes. According to their new definition, cognitive maps were psychological spaces with absolute reference frames.¹⁴¹

The current challenge with cognitive maps stems from the vague definitions of the term,¹⁴² its constant reformulation,^{143,144} and inaccurate citations of Tolman’s and O’Keefe’s previous work. At its most extreme, cognitive maps are considered structurally analogous to a cartographic map¹⁴⁵ in that they represent Euclidean spatial relations in a global format, from a top-down view, and with an allocentric frame of reference.^{146,147} While most researchers acknowledge that the cartographic map is only a yardstick for comparison,¹³⁸ at least five issues regarding cognitive maps remain. Cognitive maps may be defined with respect to level of abstraction (e.g., amodal vs modality-specific¹⁴⁸), scope (e.g., global vs local⁵⁸), metricality (e.g., Euclidean vs topological^{149,150}), perspective (e.g., orientation free, top-down, or first-person^{151,152}), and reference frame (e.g., egocentric vs allocentric, absolute vs relative¹⁵³). Consequently, different researchers have employed different tasks in order to investigate

cognitive maps.⁷⁶ An additional source of confusion is the nesting of these various terms. For example, reference frames can include a perspective, but a perspective does not necessarily assume a particular reference frame.

With respect to research on the blind population, the term cognitive map continues to be loosely applied. There are many important findings regarding the content (i.e., the amount of acquired spatial knowledge) and quality (i.e., its character or format) of blind individuals' spatial representations (see *Spatial Learning by Blind People* section). However, separate aspects of the term are conflated in discussions of whether blind people have cognitive maps. For example, researchers may use both route knowledge techniques (e.g., distance and direction estimates) and survey techniques (e.g., sketch maps) in order to probe 'cognitive map' knowledge.^{44,76,88,106,107,109,154} Performances on these tasks may appear to provide overwhelming evidence for cognitive maps in blind people. However, this inconsistency in the operationalization of the term may also represent a variety of specific spatial abilities. Thus, we recommend the use of relatively well-defined terms (e.g., metricality and reference frame) when investigating the content and quality of spatial representations in the absence of vision.

NEURAL CORRELATES OF HUMAN NAVIGATION

In order to further investigate the process of cognitive mapping, researchers have also employed neuroscientific methods. Research with animals has found that the medial temporal lobe is critical for the allocentric spatial representations (often referred to as cognitive maps) that underlie navigation.¹⁴⁰ In particular, grid cells¹⁵⁵ in the medial entorhinal cortex provide place cells¹³⁹ primarily in the hippocampus (but see Whitlock¹⁵⁶ for the parahippocampus and parietal cortex) with the coordinate system required for location-specific encoding.¹⁵⁷ Similarly, research using cell recordings in humans has identified place cells¹⁵⁸ and grid cells.¹⁵⁹ Consistent with an allocentric representation system, neuroimaging studies have found correlations between hippocampal activity and Euclidean distances between presented locations (specifically in the left anterior region¹⁶⁰), directional responses during an initial learning phase,¹⁶¹ mental¹⁶² or virtual¹⁶³ navigation along a known route between landmarks, and triangle completion.¹⁶⁴ In addition, differences in the volume of the posterior hippocampus have been related to navigation

expertise¹⁶⁵ and training¹⁶⁶ in taxi drivers and inferential pointing judgments by college students.⁶⁶ Lesion studies further confirm the role of the hippocampus for encoding locations in an allocentric reference frame.^{167–169} Several studies have dissociated this allocentric system in the medial temporal lobe with a response-based system centered in the caudate nucleus in both animals¹⁷⁰ and humans^{171–173} (for reviews see Refs 174–176). A response-based system encodes procedural knowledge such as specific action sequences during navigation.¹⁷⁰

Also supporting human spatial navigation is a scene-processing network centered around the parahippocampal place area (PPA¹⁷⁷) and retrosplenial cortex (RSC).¹⁷⁸ Both the PPA and RSC respond preferentially to scenes when compared to objects or faces.¹⁷⁷ In particular, the PPA is responsible for encoding the spatial structure of the local scene (for a review, see Ref 179). The PPA is particularly responsive to landmarks at decision points (i.e., those that are relevant for navigation⁶⁴), and the parahippocampal gyrus more generally can discriminate between large and small objects.¹⁸⁰ In contrast, the RSC is responsible for situating the local scene within the broader spatial environment (for a review, see Ref 179). In particular, the RSC integrates egocentric spatial information and may have a role in translating that information into an allocentric code.¹⁶¹ Such information includes the direction of travel at decision points⁶⁴ and, more precisely, the observer's position and heading¹⁸¹ analogous to head direction cells in rats.¹⁸²

Neural Correlates of Navigation by Blind People

Despite the advances in neuroscience research on navigation by sighted individuals, this work has been difficult to extend to blind individuals, especially for meso- and macroscale environments. Some researchers have opted to conduct the experimental task outside the MRI scanner and analyze the relationship between the structural image and task performance.¹⁸³ Others have attempted to circumvent this challenge by employing tactile (e.g., finger mazes⁴⁶ and shape recognition^{184,185}) or auditory tasks.¹⁸⁶ However, tactile tasks sometimes require movement beyond the typical button responses that can cause artifacts in the functional imaging data without appropriate control conditions.⁴⁶ Furthermore, auditory tasks have focused on spatial abilities that do not necessarily correspond to those used during navigation (e.g., sound localization without locomotion¹⁸⁷). In addition, researchers have rarely allowed

both blind and sighted participants to use their dominant modality in learning or testing within the same experiment (see discussion of the relationship between strategy, performance, and ability in the Introduction).

Studies in which blind participants used either auditory or tactile modalities have highlighted their brains' capacity for both intramodal (e.g., changes in functional areas resulting from visual deprivation corresponding to the same modality) and cross-modal (e.g., changes in functional areas resulting from visual deprivation corresponding to a different modality) plasticity^{188,189} although these two phenomena are not mutually exclusive.¹⁹⁰ Indeed, the occipital cortex (including the associative areas) can be recruited during both auditory^{191,192} and tactile^{51,52,193} tasks (for reviews, see Refs 194,195). In addition, structural imaging studies have found reduced volume in the occipital cortex for blind participants relative to sighted participants^{196,197} (for a review, see Ref 198). A deformation-based morphometry study also found that, while the early occipital cortex is reduced for blind individuals compared to sighted individuals, the associative occipital cortex is relatively large.¹⁹⁹ Although the role of the occipital cortex is different for blind and sighted individuals in general, less is known about structural and functional differences in other areas that support navigation.

Analogous to studies with sighted people, research into the neural correlates of navigation by blind people have investigated allocentric, response-based, and scene-processing networks (see Figure 3). With respect to the allocentric network centered in

the hippocampus, volumetric studies found that blind people have smaller right posterior hippocampi^{200,201} and larger right anterior hippocampi^{183,201} relative to sighted people. Fortin and colleagues¹⁸³ also found that the size of the right hippocampus was correlated with performance on a wayfinding task in a maze. The hippocampus has also been implicated for navigation through a tactile finger maze⁴⁶ and an Euclidean distance task (comparable to Morgan¹⁶⁰) using auditory cues.¹⁸⁶ These studies may appear to provide evidence for allocentrism in blind individuals. However, it should be noted that two of these studies^{200,201} did not associate hippocampal volume with a navigation task⁶⁴ or expertise.^{165,166} In addition, the correlation between hippocampal size and performance found by Fortin and colleagues¹⁸³ is based on data aggregated over blind and sighted participants for a task that did not necessarily require an allocentric reference frame. Furthermore, the imaging data from Gagnon and colleagues⁴⁶ contrasted maze navigation with rest instead of a control task that could have disentangled the effect of navigation from that of general task completion. Interestingly, to date, no studies have found activation of or volumetric differences in the caudate related to a response-based navigation system by blind people.²⁰² Several studies have also implicated the scene-processing network centered around the PPA and RSC for the haptic exploration of scenes (compared to objects¹⁸⁴) and the discrimination of object sizes.¹⁸⁵ These findings help to frame other investigations that have found activation in the parahippocampal gyrus for a tactile finger maze task⁴⁶ and navigation through a virtual environment with the aid of an SSD.⁴⁷

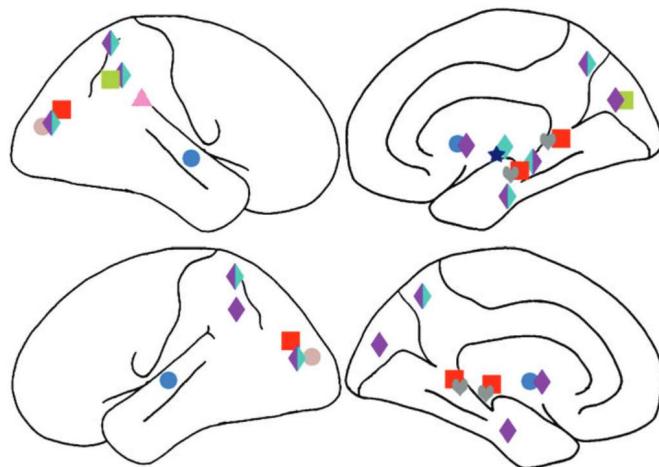


FIGURE 3 | A schematic depiction of the neural correlates (i.e., functional and structural) of navigation by the blind. Indicators are organized by study and task. The color of each indicator represents study, and the shape represents type of task. Indicators are placed over the approximate regions corresponding to each study.

	Route recognition	Judging object size	Imagined locomotion	Path integration	Shape discrimination	Wayfinding in a azeazumia	
Deutschlander et al., 2009 (Ref 205)	◆						fMRI
Kupoers et al., 2010 (Ref 47)	◆						fMRI
Wolbers et al., 2011 (Ref 184)				◆			fMRI
Gannon et al., 2012 (Ref 46)		◆					fMRI
Chan et al., 2012 (Ref 186)			◆				fMRI
He et al., 2013 (Ref 185)			◆	◆			fMRI
Halko et al., 2014 (Ref 204)				◆			fMRI
Kober et al., 2014 (Ref 203)				◆			EEG
Fortin et al., 2008 (Ref 183)						★	Volumetric

Previous research has also identified a variety of other brain regions (e.g., parietal and occipital cortices) that were active during navigation tasks by blind people (see Figure 3). Specifically, the right inferior parietal cortex was active during an Euclidean distance task using auditory cues,¹⁸⁶ and the posterior parietal cortex was active during navigation through a virtual environment using a SSD.⁴⁷ In addition, the occipital cortex was active during haptic⁴⁷ (uncorrected⁴⁶) and imagined²⁰³ navigation. Other areas may be related to navigation by blind people, but more research is needed before these can be tied to specific spatial knowledge constructs (precuneus and fusiform gyrus⁴⁷; temporal parietal junction²⁰⁴; and superior temporal gyrus²⁰⁵). The recruitment of these areas by different modalities (e.g., auditory and tactile) may suggest the functional reorganization of cortical areas in order to support navigation.⁴⁷ This is consistent with results from Wolbers and colleagues¹⁸⁴ in which functional connectivity analysis indicated lack of significant connections between the occipital and posterior parahippocampus for the haptic discrimination task. Taken together, these results may support theories of amodal spatial representation (rather than visual recoding) in blind participants' brains.

FUTURE CONSIDERATIONS

Technological Advances for Navigation Assistance

There are three different technological approaches to navigation assistance for blind people. First, noninvasive technologies including SSDs exploit the brain's natural ability to adapt in response to the environment.^{188,206} Second, invasive technologies directly stimulate regions of the visual system with the aid of a prosthesis in order to bypass damaged areas.^{207–212} In these two cases, the technologies attempt to bypass the missing sense in order to complement the user's existing sources of spatial information. Unlike SSDs, invasive technologies are not targeted towards congenitally blind people but are found to be effective for adventitiously blind people given that these devices require a developed visual system and/or prior visual experience.²¹³ Indeed, studies using transcranial magnetic stimulation (TMS) in the visual cortex have demonstrated that elicited vision-like sensations (i.e., phosphenes) increase with remaining visual acuity in adventitiously blind participants²¹⁴ and may not occur for congenitally blind participants.¹⁹⁸ Furthermore, Garcia and colleagues²¹⁵ found that a retinal prosthesis did not provide

sufficiently coherent or precise information for navigation. Third, general navigation aids can provide abstracted spatial information to the user using one of his/her functioning senses (e.g., GPS devices). Unlike SSDs and invasive technologies, these general aids can potentially be used by people with or without vision. Despite the large number of conceptual papers on this topic,^{216–225} we will focus our discussion on the few examples of SSDs that have been empirically tested in the context of navigation. For more comprehensive reviews of technological navigation aids and SSDs, see Refs 4, 5, and 226.

SSDs translate visual information into tactile information, auditory information, or both in a non-invasive manner.^{3,5,227,228} These devices have been available for several decades, but they have not been widely adopted by the blind population^{6,229,230} (but see Ref 231). Recently, researchers have investigated the potential of these technologies for navigation by blind people.^{47,129,232–234} At the same time, evidence from neuroscience regarding the brain's capacity for functional reorganization^{47,54,184,235} suggests flexibility with respect to the channels through which perceptual information can be processed. Indeed, congenitally blind participants using SSDs recruit visual areas to recognize sounds, shapes, and movement^{187,236} (see *Neural Correlates of Navigation by Blind People* section). This is consistent with the view that the brain considers information in a task-dependent, rather than a modality-dependent, manner.²⁰⁶

Since 2000, many researchers have investigated the use of SSDs for locomotion and wayfinding assistance in indoor and outdoor, real and virtual, environments using auditory and tactile feedback.^{233,234,237–266} While many of these SSDs are technically impressive, their evaluation too often relies on qualitative data,^{237,238,242–245,247,251,252} a very small number of blind participants (i.e., five or less),^{239,241,248,250,260,262,263,267} or only blindfolded sighted participants.^{233,240,246,249,261,264,265} However, with an adequate number of blind participants, some researchers have demonstrated that blind people are capable of using some devices for navigation.^{234,253,254,256–258,268,269}

Some of these SSDs have been tested in the context of locomotion with varying success. For example, the Tongue Display Unit (TDU) transforms visual information into electrotactile stimulation that conveys the position of obstacles in the surrounding environment. Blind participants have been shown to effectively use the device in order to navigate a virtual maze⁴⁷ and even outperform blindfolded sighted participants in a high contrast, life-size, obstacle

course.²⁰⁰ Similarly, Dunai and colleagues²⁶⁸ showed that training with their Acoustic Prototype allowed blind participants to perceive and avoid objects in indoor and outdoor obstacle courses. In addition, the EyeCane is a device for transforming distance information into both sounds and vibrations.²⁷⁰ The EyeCane has been successfully used in a virtual obstacle avoidance task²⁷⁰ and in a real life-size Hebb-Williams maze.¹²⁹ Despite the recent achievements of both TDUs and the EyeCane, participants using these devices had some difficulties avoiding obstacles near the ground.^{129,271}

SSDs have also been developed for wayfinding assistance. For example, Marston and colleagues²⁵³ successfully directed blind participants along real world paths using different auditory displays. Similarly, Kalia and colleagues²⁵⁴ conveyed distance information to blind and blindfolded sighted participants with the aid of a digital map and synthetic speech. In addition, some researchers have shown that auditory and tactile virtual reality training can facilitate wayfinding in a corresponding real environment.^{258,269} Together these studies suggest that SSDs can benefit blind people during navigation. However, Loomis and colleagues⁶ have argued that the success of SSDs is dependent on the extent to which the information they provide is relatively simple and task-specific. Before SSDs can be widely applied, we need to gain a better understanding of the navigation abilities of the blind population.

Heterogeneity in the Blind Population

Any intervention intended to support navigation by blind people requires an understanding of their needs as a group and as individuals. Heterogeneity in the blind population has created many difficulties for researchers^{13,272} and cross-study comparisons.¹⁸⁹ These difficulties stem from at least five methodological factors, including sample size, type of impairment, age of onset, level of education and intelligence, and level of orientation and mobility (for a review, see Ref 75). Many studies have reported findings regarding the navigation performance of blind people using small sample sizes (e.g., eight,¹⁰⁹ seven,¹¹ six,⁸⁰ two,⁹² and one⁸⁴), which makes it difficult to generalize from one study to another. Type of impairment and age of onset can also lead to challenges with the assignment of participants to experimental groups. Moore and colleagues²⁷³ estimate that 75% of those considered blind have some remaining vision. For example, people with only light perception are often classified as totally blind.²⁷⁴ Past studies have found performance differences related to

both type of impairment (e.g., lower performance for retrorenal fibroplasia²⁷⁵) and age of onset.¹¹⁰ In addition, level of education and intelligence has been found to correlate with performance on a map task²⁷⁵ and sometimes creates potential confounds.³⁹ Finally, assessments of level of orientation and mobility at the time of testing may be an important factor to consider when studying the acquisition of spatial knowledge.⁸³

Navigation Strategies

The study of navigation strategies provides an innovative way of addressing challenges associated with the heterogeneous nature of the blind population. Previous research has required blind and sighted participants to adopt similar strategies in order to complete a particular task. However, this approach has led to difficulties in extracting consistent patterns in spatial knowledge acquisition during navigation. While the number of studies on navigation strategies in blind people is limited,^{8,16,276} they suggest that performances on spatial tasks are strongly associated with strategy choice for both blind and sighted individuals. Such investigations were also limited in the past given methodological challenges such as collecting path information and the manual classification of strategies (but see Ref 35).

Originally, search strategies were classified by Hill and Ponder²⁷⁷ as part of orientation and mobility training. The perimeter (e.g., walking along the walls of a room) and gridline (e.g., walking parallel transects from one wall to the opposite wall) strategies allowed the visually impaired to systematically explore novel environments. After initial learning, Tellevik²⁷⁸ found that blindfolded sighted participants (all mobility instructors) tended to shift from the perimeter or gridline strategies to a reference point strategy (i.e., walking from a known location to each target object and back). Hill and colleagues²⁷⁶ further characterized three reference point strategies as object-to-object, object-to-wall, or object-to-start. They found that participants who chose one of these three strategies also provided the most accurate direction estimates irrespective of level of visual impairment.²⁷⁶ However, a subsequent study showed that blind participants used these reference point strategies less often than blindfolded sighted controls and instead opted for a cyclic search pattern (i.e., walking to each object sequentially⁸). In this case, the cyclic strategy was associated with worse performance than the reference point strategy.^{8,279} Schinazi¹⁶ replicated the relationship between the reference point strategy and better

performances on a variety of spatial tasks. However, when visual information is available, the cyclic strategy was also related to better performance.

CONCLUSION

The systematic testing of scientific models sometimes requires the adaptation of existing frameworks in order to incorporate findings from disparate fields. In this review, we have attempted to bridge spatial cognition and visual impairment literatures, including recent advances in neuroscience and technology, in order to gain a better understanding of the navigation abilities in blind people. Towards this end, we proposed that future research should allow for blind and sighted individuals to adopt different strategies that do not artificially limit their potential. We also proposed three models of spatial knowledge acquisition by blind and sighted people and attempted to

characterize previous research in these terms. This procedure highlighted the importance of measuring spatial learning over time in order to assess learning potential in the absence of vision. This longitudinal approach also allows for the investigation of hypotheses regarding amodal spatial representation. Along with existing studies on the functional equivalence of different perceptual modalities, we proposed a line of research on the Bayesian integration of spatial cues from multiple modalities used by blind people. This is complemented by a review of the neural correlates of navigation by blind people within the context of functional reorganization. The topic of functional reorganization was also considered in light of new developments for SSDs that were specifically designed to aid navigation by blind individuals. Future considerations also included methodological issues resulting from heterogeneity in the blind population and the ways in which they may be addressed with research on navigation strategies.

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