Neuroscience and Biobehavioral Reviews 140 (2022) 104797

Contents lists available at ScienceDirect

Neuroscience and Biobehavioral Reviews

journal homepage: www.elsevier.com/locate/neubiorev

Review article

Cognitive map formation supported by auditory, haptic, and multimodal information in persons with blindness

Loes Ottink[a,*], Hendrik Buimer[a,1], Bram van Raalte[a], Christian F. Doeller[b,c], Thea M. van der Geest[d], Richard J.A. van Wezel[a,e]

[a] Donders Institute, Radboud University, Nijmegen, the Netherlands
[b] Psychology Department, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany
[c] Kavli Insitute for Systems Neuroscience, NTNU, Trondheim, Norway
[d] Lectorate Media Design, HAN University of Applied Sciences, Arnhem, the Netherlands
[e] Techmed Centre, Biomedical Signals and System, University of Twente, Enschede, the Netherlands

ARTICLE INFO

Keywords:
Cognitive maps
Spatial navigation
Persons with blindness
Non-visual sensory modalities
Auditory
Tactile
Haptic
Multimodal
Route representation
Survey representation

ABSTRACT

For efficient navigation, the brain needs to adequately represent the environment in a cognitive map. In this review, we sought to give an overview of literature about cognitive map formation based on non-visual modalities in persons with blindness (PWBs) and sighted persons. The review is focused on the auditory and haptic modalities, including research that combines multiple modalities and real-world navigation. Furthermore, we addressed implications of route and survey representations.

Taking together, PWBs as well as sighted persons can build up cognitive maps based on non-visual modalities, although the accuracy sometime somewhat differs between PWBs and sighted persons. We provide some speculations on how to deploy information from different modalities to support cognitive map formation. Furthermore, PWBs and sighted persons seem to be able to construct route as well as survey representations. PWBs can experience difficulties building up a survey representation, but this is not always the case, and research suggests that they can acquire this ability with sufficient spatial information or training. We discuss possible explanations of these inconsistencies.

1. Introduction

Spatial navigation and wayfinding in familiar and unfamiliar environments are important but complex activities. To facilitate wayfinding, we need to adequately remember or mentally represent the environment. Spatial information from the environment can be represented in a mental or cognitive map (Burgess et al., 2002). Such a cognitive map incorporates for example specific locations, routes, distances and directions between locations into a representation (Deuker et al., 2016; Eichenbaum et al., 1999; Foo et al., 2005; Morgan et al., 2011). It can furthermore allow for an allocentric (environment-centred, map-like, having an overview in mind) as well as an egocentric (body-centred, route-like, turn-by-turn) perspective (Burgess et al., 2002).

Cognitive map research is often based on visual information. Input from this sensory modality, however, is not available to persons with blindness (PWBs). They rely on non-visual sensory modalities, such as auditory and haptic information. The visual modality differs from the auditory and haptic modalities on several aspects regarding conveying spatial information and how it contributes to cognitive map formation. For instance, visual information allows for simultaneous perception of abundant information in the environment (Millar, 1988; Thinus-Blanc and Gaunet, 1997), and for conveying spatial relationships and contextual background in parallel (Pasqualotto and Proulx, 2012). The auditory and haptic modalities, however, are less suitable for parallel communication of spatial information, may lack contextual cues, and are perceived sequentially (Pasqualotto and Proulx, 2012; Schinazi, Thrash, and Chebat, 2016). Furthermore, visual spatial information is more stable and allows for more precise localisation of nearby as well as distant objects (Schinazi et al., 2016; Thinus-Blanc and Gaunet, 1997). Haptic information only conveys information about nearby objects, and auditory information is much less reliable. Vision stabilises the surroundings while the perceiver or an object moves around, while audition

---

* Correspondence to: Heijendaalseweg 135, P.O. Box 9010, 6500 GL Nijmegen, the Netherlands.
E-mail address: loes.ottink@donders.ru.nl (L. Ottink).

[1] Present affiliation: Vilans Centre of Expertise for Long-term Care, Utrecht, The Netherlands

https://doi.org/10.1016/j.neubiorev.2022.104797
Received 22 March 2022; Received in revised form 23 June 2022; Accepted 24 July 2022

is more variable and unreliable when for instance a sound source itself moves as well (Thinus-Blanc and Gaunet, 1997). Moreover, not all objects emit sound. Vision allows for direct and stable perception of objects and spatial relationships in the surrounding environment, while perception of such information through auditory is more indirect and requires inference. Furthermore, lack of visual experience may reduce multisensory integration, also of non-visual modalities for spatial tasks (Pasqualotto and Proulx, 2012). Vision calibrates the other senses, much more than the other way around, however, this does not mean that multisensory integration cannot develop without the visual sensory modality (Pasqualotto and Proulx, 2012; Thinus-Blanc and Gaunet, 1997).

This review sought to give a concise overview of literature about cognitive map formation based on non-visual modalities. We first will give a short outline of literature based on visual information. The main body of the review is then focused on the auditory and haptic modalities, including research that combines multiple modalities and real-world navigation. We have only included studies that investigated adults who are blind, or in some cases severely visually impaired. Furthermore, the role of different navigational strategies and representations are addressed.

Cognitive maps were first introduced as imaginary maps by Trowbridge in 1913, and later as cognitive maps by Tolman in 1948, as a mental representation of an environment in the rat brain. From there, neuroscience research on spatial memory and cognitive map formation in rodents has advanced using single-cell recordings. Through this technique, several types of neurons have been discovered that are active in relation to the environment an animal is currently in (Grieves and Jeffery, 2017; Moser et al., 2008), such as place cells, grid cells, boundary cells, and head direction cells. These cells form the neural basis of cognitive maps (Grieves and Jeffery, 2017). Place cells are located in the hippocampus and fire when the animal is in one specific location in an environment (Moser et al., 2008; O'Keefe, 1976). Specific kinds of place cells, boundary cells in the subiculum, fire in relation to a boundary of a space, for example a wall (O'Keefe and Burgess, 1996; Stewart et al., 2014). Grid cells in the entorhinal cortex are also active in specific locations, but these have multiple firing fields that form a hexadirectional grid covering the environment (Hafting et al., 2005; Moser et al., 2008). Head direction cells have been found in several (sub) cortical areas, and are active when the head of the animal points in a certain direction (Grieves and Jeffery, 2017). The combined signalling of these cells contribute to the animal's spatial orientation, and to the integration of spatial information into a cognitive map of the environment. There is also evidence for such spatially tuned cells in the human brain. Similar to place cells in the rat brain, some neurons in the human hippocampus respond at certain locations during a spatial navigation task (Ekstrom et al., 2003). Moreover, hippocampal activity has been found to be related to boundaries in an environment (Bird et al., 2010). Evidence for grid cell-like activity has been found in a network including the entorhinal cortex of humans (Doeller et al., 2010). Furthermore, head direction seems to be encoded by the thalamus and subiculum (Kim and Maguire, 2019).

One step further, several neuroimaging studies show neural representations of spatial information such as distances in the human hippocampus, suggesting the formation of a cognitive map in this area (Deuker et al., 2016; Howard et al., 2014; Morgan et al., 2011). Besides neuroimaging techniques, a large portion of literature have used behavioural measures to investigate cognitive map formation. For instance, formation of a spatial representations based on visual information has been demonstrated using tasks such as reproduction of routes (Maguire et al., 1997) and map layout (Foo et al., 2005), recall of specific locations (Foo et al., 2005; Maguire et al., 1999), estimation of distances (Deuker et al., 2016; Morgan et al., 2011), and estimation of directions (Foo et al., 2005). In this review, we will not further describe research based on visual information (for a review, see e.g. Burgess et al., 2002; Eichenbaum et al., 1999; Epstein et al., 2017). Nevertheless, various behavioural measures have also been used in studies about cognitive map formation by persons with blindness (PWBs), based on non-visual sensory modalities. In the current review, we give an overview of this literature. Most of the studies only focused on PWBs. Some literature also compares PWBs to sighted persons. We have described these results in the current review, however, not all literature has included this comparison. Moreover, some studies make a distinction between early PWBs (blindness onset before age 3) and late PWBs (blindness onset later than age 3). We have only reported results that involve PWBs who were severely visually impaired or legally blind, and sighted persons who were blindfolded (if applicable).

We have categorised the studies based on auditory and haptic modalities. Research about the auditory modality was divided into studies that use verbal sounds and non-verbal sounds. The haptic modality includes tactile information, as they both entail stimulation or exploration through touch. Tactile refers to materials or passive stimulation, while haptic entails active exploration of for instance a tactile map or object. We will furthermore discuss literature that uses multimodal approaches and combines two or more modalities, as well as studies involving real-world navigation. An overview of environments or stimuli in the different modalities, and how they are divided in this review, is given in Box 1. See Table 1 for the number of papers included about each modality. A table with details on empirical studies (participant numbers of (early and late) PWBs and sighted persons, age), as well as the applied search strategy can be found in the supplemental material.

This review furthermore makes a distinction between the different types of spatial information that are used to test the knowledge of the spatial environment or to externalise cognitive maps after exploring an environment. These types of spatial information include route information, map layout, specific locations, distances between locations, and directions. These are set out for each modality (auditory, haptic, multimodal, and real-world navigation). Examples of behavioural measures for each information type used in literature are given in Box 2. One important thing to note here, however, is that there is a large diversity in research designs and how cognitive maps or specific spatial information types are externalised. This might result in some (seemingly) ambiguous or contradictory findings.

Besides cognitive map formation based on different sensory modalities, the role of navigational strategies are also explored in this review. In general, a distinction can be made between a route and survey strategy, based on route- and survey-type mental representations. Whether someone can form a route or survey representation of an environment, and whether someone uses a route or survey strategy during navigation or spatial tasks seems to affect their navigational abilities (Prestopnik and Roskos-Ewoldsen, 2000). Survey representations or strategies are based on having a map-like overview in mind. Such map-like mental representations are flexible and allow for example for inferring detours or shortcuts (Prestopnik and Roskos-Ewoldsen, 2000). Survey representations somewhat relate to an allocentric perspective (Klatzky, 1998; Zhong, 2016), which is based on relative positions to distant landmarks, or between landmarks. Route representations or strategies are based on having a mental overview of one route, and thinking from waypoint to waypoint on the route (Prestopnik and Roskos-Ewoldsen, 2000). These somewhat relate to an egocentric perspective (Klatzky, 1998; Zhong, 2016), which is based on a viewpoint from one's own body or location, relative to nearby landmarks. The terms survey and allocentric, and route and egocentric, are not identical, however, they are in some studies used interchangeably, since a survey representation can allow for an allocentric perspective, and a route representation can allow for an egocentric perspective (Prestopnik and Roskos-Ewoldsen, 2000; Zhong, 2016). It is thought that many PVIs experience more difficulties in forming survey representations compared to sighted persons, and compared to a route representation (Gaunet, Martinez, and Thinus-Blanc, 1997; Giudice, 2018; Schinazi et al., 2016; Thinus-Blanc and Gaunet, 1997). To these individuals, autonomous navigation is often challenging, however, it can be

Box 1
Overview of environments or stimuli in the different modalities, and how they are divided in this review.

Auditory. Studies that investigate cognitive map formation based on auditory information are divided into experiments with verbal and non-verbal feedback. Verbal feedback is for example verbal instructions during navigation, or experiments include making spatial judgments after hearing a spatial description. Studies that provide non-verbal feedback, mainly use a virtual auditory environment with iconic sounds.

Haptic. Most literature about haptic information, makes use of tactile maps, or tactile paths, that participants can explore with their hand. Another kind of experiment includes making spatial judgments after exploring the arrangement of a set of tactile objects.

Multimodal. Some literature combines auditory and tactile information into audio-tactile maps. These mostly are tactile maps supported by auditory feedback.

Real-world navigation. Navigation tasks where participants have to physically walk, combine proprioceptive information with at least one other modality. Such tasks can include for instance navigating routes in- or outside buildings, exploring mazes, or walking a route supported by auditory instructions or a tactile map.

Table 1
Number of included papers of each section. Some papers contain results about multiple sections. A table with details on empirical studies (participant numbers of (early and late) PWBs and sighted persons, age), as well as the applied search strategy can be found in the supplemental material.

Section	Number of papers
Total (excluding introduction)	69
Auditory	17
Non-verbal	8
Verbal	11
Haptic	38
Multiple modalities	22
Real-world navigation	17

improved by training in orientation and mobility (O&M; Bozeman and McCulley, 2010; Giudice, 2018). Nevertheless, to persons who rely on non-visual information, the orientation component of O&M training is generally challenging (Brock and Jouffrais, 2015; Thinus-Blanc and Gaunet, 1997). Here, issues possibly arise because vision provides more spatial information at once compared to other sensory modalities (Thinus-Blanc and Gaunet, 1997). The orientation component involves processes such as wayfinding, mental rotation, spatial updating, computing detours and finding shortcuts, and cognitive map formation (Bozeman and McCulley, 2010). These have often, but not always, been reported to be challenging based on non-visual sensory input (Bozeman and McCulley, 2010; Gaunet et al., 1997; Pasqualotto and Newell, 2007; Schinazi et al., 2016; Thinus-Blanc and Gaunet, 1997; Ungar, 2000). The abilities to construct and use route and survey representations by PWBs and sighted persons will be further explored in this review.

2. Cognitive maps based on auditory information

In literature addressing cognitive map formation based on auditory information, a distinction can be made between verbal and non-verbal feedback.

2.1. Non-verbal auditory feedback

Using non-verbal, mostly iconic sounds, participants have for instance explored 2D maps, or performed navigation tasks in a virtual environment. Knowledge about different kinds of spatial information have been used to assess the formation of cognitive maps. This has been tested using for example tasks to find specific routes and shortcuts, reach target locations, identifying correct layouts, and estimating distances between locations. Some research furthermore looked at how well the cognitive map can support real-world navigation. Representations of directions in a cognitive map have not specifically been studied using the auditory modality. Besides, most studies addressing the auditory modality focused on PWBs and did not include sighted participants. If the comparison of PWBs and sighted persons was made, we have described this in the following section.

2.1.1. Route

Multiple studies show that persons with blindness (PWBs) can build a cognitive map of a comprehensive virtual environment with mostly non-verbal auditory feedback (Connors et al., 2014b, 2014a; Sánchez et al., 2010), and after exploring routes with verbal as well as non-verbal feedback (Aziz, Stockman, and Stewart, 2022). After exploring the environment, participants were able to retrieve route information from their cognitive map. Their cognitive maps furthermore allowed to determine alternative routes to reach target locations, which indicates sound and flexible spatial representations (Connors et al., 2014b, 2014a).

2.1.2. Layout

Exploration of auditory geographic maps has been found to lead to accurate mental representations of the overall map layout (Delogu et al.,

Box 2
Examples of behavioural measures for each information type used in literature.

Route: walking a route, reproduction of a route by drawing or building
Layout: reproduction of a layout by drawing or building, choosing the correct model out of several incorrect ones, arrange objects into the correct configuration
Locations: location recall, reaching targets in environment, locational judgments about objects in an arrangement
Distance: estimating absolute or relative distances between locations
Direction: pointing task from start location, own location, or other location

2010). Early PWBs, late PWBs, as well as sighted persons have been able to detect the correct tactile version of the map amongst several incorrect ones. Furthermore, both PWBs and sighted persons could reproduce the layout of an auditory map in detail, indicating thorough spatial knowledge (Loeliger and Stockman, 2014). In this study, however, verbal and non-verbal auditory feedback types were mixed, making it challenging to determine which type contributed to what spatial knowledge exactly (Loeliger and Stockman, 2014).

2.1.3. Locations

After exploring an auditory environment, PWBs had a good representation of specific locations in the space (Aziz et al., 2022; Connors et al., 2014b, 2014a; Halko et al., 2014), as well as sighted persons (Aziz et al., 2022). Interestingly, participants who explored such an environment freely, seemed to have a more robust cognitive map and performed better at location recall tasks than participants who were guided by researchers and only navigated predetermined routes (Connors et al., 2014b, 2014a).

2.1.4. Distance

It thus seems that PWBs and sighted persons can build an accurate and flexible cognitive map by free exploration of a virtual environment with only auditory feedback. It appears, however, that early PWBs have a compressed representation of distances in an environment compared to late PWBs and sighted persons (Gori et al., 2017). This may arise because of a less accurate Euclidean representation or the tendency to use an egocentric perspective in early PWBs (Gori et al., 2017).

2.1.5. Support real-world navigation

Moreover, exploring an auditory version of an environment has been shown to support wayfinding in the real-world space in a subset of studies. PWBs showed good transfer of spatial knowledge from the virtual to the real-world environment (Connors et al., 2014b, 2014a; Loeliger and Stockman, 2014; Sánchez et al., 2010). For instance, they could use the map layout learned in the virtual environment to reach target locations in the real environment (Connors et al., 2014b, 2014a). Hereby, ambient sounds in the virtual environment seemed to improve route navigation performance in the real-world (Loeliger and Stockman, 2014).

Overall, although there is a relatively low number of studies that focused on non-verbal auditory information, they suggest that PWBs can form accurate spatial representations using only this modality. Participants have been able to find routes and shortcuts, efficiently reach target locations, and identify the correct layout, after exploring a map or virtual environment using solely non-verbal auditory information. This knowledge also transfers well into the real world. Nevertheless, early PWBs seem to have compressed representations of distances compared to late PWBs and sighted persons based on this modality.

2.2. Verbal auditory feedback

Cognitive map formation has furthermore been studied using verbal auditory feedback, such as verbal instructions during navigation, or providing a spatial verbal description.

2.2.1. Route

Early PWBs build up a correct representation of routes from exploration of a virtual environment with verbal feedback (Guerreiro et al., 2017), and with verbal as well as non-verbal feedback (Aziz et al., 2022). The representations, however, were sequential, and might not always have been suited to allow people to infer survey knowledge such as distances between points that are not experienced sequentially (Guerreiro et al., 2017). Furthermore, a verbal description could be distracting instead of supporting when it is combined with direct route navigation (Espinosa and Ochaita, 1998).

2.2.2. Layout

When exploring an auditory environment with verbal as well as non-verbal feedback, both PWBs and sighted persons could reproduce the layout of the map in detail, indicating comprehensive spatial knowledge (Loeliger and Stockman, 2014). Here it is not entirely clear, however, which type of feedback (verbal or non-verbal) contributed to what spatial knowledge exactly. Participants could furthermore accurately reconstruct the layout of an environment after listening to a verbal description (Schmidt et al., 2013). Sighted participants, however, formed better representations than PWBs (Schmidt et al., 2013).

2.2.3. Locations

Similarly, after exploring routes in an auditory environment with verbal as well as non-verbal cues, PWBs and sighted participants accurately mentally represented particular locations along the route (Aziz et al., 2022).

2.2.4. Distance

When navigating an environment with verbal auditory feedback, PWBs could build up an accurate cognitive map. This map included accurate representations of distances between locations in the environment (Cobo et al., 2017; Guerreiro et al., 2017). After exploring a virtual room with a cane that gives verbal feedback (e.g., feedback is provided about objects and obstacles such as walls, in the direction a person points the cane towards), people seemed to have an accurate representation of distances within the room (Cobo et al., 2017).

Besides active exploration of an environment, there is also literature that assessed the formation of spatial representations after listening to verbal spatial descriptions. It was suggested that early PWBs, late PWBs, as well as sighted persons are able to form mental representations from the description, which included distance representations (Noordzij et al., 2006; Steyvers and Kooijman, 2009). Early PWBs, however, were not always capable of such representations of distances between locations, contrasting to late PWBs and sighted persons (Afonso et al., 2010). When participants also heard non-verbal sounds coming from respective locations, the differences between early PWBs and the other groups diminished (Afonso et al., 2010). This suggests that verbal descriptions only might not always be sufficient to build an effective cognitive map.

Taken together, literature indicates that providing verbal feedback is adequate to construct accurate mental representations of routes, locations, distances and general layout. Furthermore, during navigation, audition can provide information about in which direction (and approximately how far) a landmark is through sound localisation (Després et al., 2005; Finocchietti et al., 2017), however, representations of directions have not been investigated in this modality. Solely verbal spatial descriptions have been shown to not be sufficient to build up distance representations in early PWBs. Considering both verbal and non-verbal auditory information, PWBs and sighted persons built up equally accurate representations of routes, layout and locations. Early PWBs, however, experienced somewhat more difficulties representing distance information compared to late PWBs and sighted persons. This might have arisen due to the survey nature of distances, where persons without visual experience might encounter more difficulties. Furthermore, the number of studies that specifically assessed cognitive map formation using only auditory information is low compared to the other modalities. Besides, not all types of spatial information have been addressed in the auditory modality. Therefore, it may be premature to draw robust conclusions.

2.3. Cognitive maps based on haptic information

To assess mental representations of haptic or tactile spatial information, studies have used simple and complex map or route navigation tasks as well as simple table-top tasks involving tactile objects. Tasks were considered simple when they involved for instance tracing routes that have one or two turns, or making spatial judgments about arrangements of three tactile objects. Routes with more segments, elaborate maps or configurations of multiple objects, as well as mental rotation were used in more complex spatial tasks. In a task involving mental rotation, participants had to imagine their body rotates, and then for instance estimate the direction towards another location from this new position. Such simple and complex tasks tested spatial representations through route learning, reconstruction of general map or object layout, and tested knowledge about specific locations, distances and directions. Besides, some of this research also looked at how well exploration of tactile maps can support real-world navigation.

2.3.1. *Route*

Considering mental representations of routes from haptic information, there are few but contradictory results. Persons with blindness (PWBs) showed better route learning than sighted persons when using a visual-to-tactile sensory substitution device on the tongue (Kupers et al., 2010). PWBs also accurately recalled routes conveyed by vibrational cues on a touchpad, however, this was not compared to performance of sighted persons (Grussenmeyer et al., 2016). In comparison, when having to find routes in tactile mazes, sighted persons needed fewer trials and were better at circumventing dead ends than PWBs (Gagnon et al., 2010). Visual experience may be beneficial when having to explore a small-scale tactile environment and find routes between targets (Gagnon et al., 2010). The dissimilar outcomes in these studies might have arisen due to the differing complexities. Finding routes in a maze is a more complicated task than merely learning predetermined routes. Furthermore, the method in which haptic information was conveyed is different in these two studies. Moreover, results from two studies might not be enough to draw conclusions about differences in haptic route learning between PWBs and sighted persons. Nevertheless, both groups seem to construct quite accurate representations of complex routes.

2.3.2. *Layout*

Visuo-spatial imagery, advanced by visual experience, may promote the development of an allocentric spatial representations of tactile routes as well as maps or configurations. Therefore, PWBs may be restricted in processing complex tactile maps (Fortin et al., 2006; Gagnon et al., 2010; Lehtinen-Railo and Juurmaa, 1994), and representing tactile object configurations (Gaunet et al., 1997). After extensive training with small-scale tactile maps, however, PWBs and sighted persons formed cognitive maps including overall map layouts comparably well (Gagnon et al., 2012; Miao et al., 2017; Palani et al., 2022; Picard and Pry, 2009). Therefore, allocentric spatial knowledge and cognitive map formation may not be necessarily limited to persons who have visual experience (Gagnon et al., 2012; Palani et al., 2022). Furthermore, layout representations in blind participants were better after exploring a tactile map compared to a verbal description (Brayda et al., 2019).

2.3.3. *Locations*

Considering specific locations in a tactile environment, PWBs as well as sighted persons have been suggested to incorporate learned locations into their cognitive maps (Hollins and Kelley, 1988; Papadopoulos et al., 2012; Thinus-Blanc and Gaunet, 1997). Not all studies, however, report appropriate location representations in persons without visual experience. For instance, early PWBs constructed less accurate representations than sighted persons but not late PWBs (Iachini et al., 2014), and in other studies even to late PWBs (Pasqualotto and Newell, 2007) as well as to sighted persons (Gaunet et al., 1997). The difficulties experienced by early PWBs became especially clear when mental rotation was required to perform well on a spatial tasks involving specific object locations (Gaunet et al., 1997; Pasqualotto and Newell, 2007).

2.3.4. *Distance*

When addressing representations of distances between locations of a tactile environment, not all literature agrees. For instance, early PWBs and sighted persons performed similarly when estimating distances between table-top tactile objects (Thinus-Blanc and Gaunet, 1997). Furthermore, PWBs seemed to have better mental distance representations after tracing lines using vibrational cues on a touchpad compared to sighted persons (Grussenmeyer et al., 2016). Early PWBs, however, have shown more difficulties in accurately representing distances compared to late PWBs and sighted persons in other literature (Afonso et al., 2010; Blanco and Travieso, 2003; Cattaneo et al., 2008). Furthermore, PWBs seem to underestimate long distances, but overestimate short distances (Klatzky et al., 1995; Lederman et al., 1985). This would suggest formation of a route representation, while the opposite was found in sighted persons, suggesting a survey representation (Klatzky et al., 1995; Lederman et al., 1985).

It thus seems that PWBs, especially early PWBs, can build up a slightly less accurate distance representation from tactile object information than sighted persons. One distinction that could be made here is regarding mental rotation. Spatial tasks that involve mental rotation might be more difficult for early PWBs, since they mostly employ egocentric or movement-based strategies, compared sighted persons, who more often employ allocentric, or spatial-based strategies (Lederman et al., 1985; Thinus-Blanc and Gaunet, 1997; Ungar, 2000). The cognitive load to perform well when a task involves mental rotation is higher when a person uses an egocentric strategy (Ungar, 2000). Furthermore, visual experience has been suggested to promote visual mental imagery, which in turn seems to be involved in the ability to perform well on tasks involving mental rotation (Gaunet et al., 1997). On less complex spatial tasks, however, which do not require mental rotation or spatial inference (inference of spatial information that is not directly available), an egocentric strategy may be sufficient for PWBs to perform equally well as, or even better than sighted persons (Klatzky et al., 1995; Loomis et al., 2001; Thinus-Blanc and Gaunet, 1997; Ungar, 2000).

2.3.5. *Direction*

PWBs, especially early PWBs, have also shown to experience more problems in estimating directions between tactile locations compared to sighted persons. They did build up a representation of this feature, but a less robust and accurate one than late PWBs and sighted persons (Brambring, 1976; Chiesa et al., 2017; Hollins and Kelley, 1988; Thinus-Blanc and Gaunet, 1997). However, PWBs have also been reported to form equally accurate mental representations of directions as sighted persons (Giudice, Betty, and Loomis, 2011; Palani et al., 2022).

2.3.6. *Support real-world navigation*

Overall, literature suggests that PWBs can form cognitive maps from haptic information, however, especially early PWBs seem to experience somewhat more difficulties than sighted persons. Tactile maps or small-scale tactile models have been useful in investigating and constructing spatial knowledge in PWBs (Blades et al., 2002; Jacobson and Kitchin, 1995; Passini and Proulx, 1988; Picard and Pry, 2009). Besides the ability to form spatial representations per se, it is valuable to address whether tactile map exploration could improve actual navigation and wayfinding. A subset of studies has investigated this, suggesting that tactile maps can support wayfinding and efficient navigation in the real world (Blades et al., 2002; Caddeo et al., 2006; Cattaneo et al., 2008; Espinosa and Ochaita, 1998; Passini and Proulx, 1988; Picard and Pry, 2009; Ungar et al., 1997). Tactile maps might even give PWBs a better concept of an environment than direct experience (Caddeo et al., 2006; Jacobson, 1998; Ungar, 2000). Nevertheless, there are differences between people in effectiveness of tactile maps in supporting real-world navigation, which are suspected to arise because of differences in exploration strategies. Therefore, people who perform poorly on using tactile maps could be trained to use a more effective strategy (Ungar, 2000).

An important consideration in this line of research, is that there is a substantial difference between learning a small-scale map, and directly experiencing a real-world environment. A tactile map is a simplified model of a real-world environment, and omits irrelevant information (Ungar, 2000), even more so than most auditory virtual environments (Aziz et al., 2022; Connors et al., 2014a, 2014b; Halko et al., 2014; Sánchez et al., 2010). In addition, a tactile map can be explored much faster, and is perceived more allocentrically (from above) than a large-scale environment (Ungar, 2000). In large-scale spaces, more (relevant and irrelevant) information is perceived, and the exploration time is much longer. This increases the effort it takes to integrate relevant information into a map-like representation (Gagnon et al., 2010; Iachini et al., 2014). Especially early PWBs experienced difficulties in constructing survey representations, and this was more prominent in large-scale compared to small-scale spaces (Iachini et al., 2014).

Overall, PWBs as well as sighted persons formed accurate representations of routes, map layout, locations, distance and direction based on haptic information, although accuracy was sometimes lower for PWBs. Moreover, tactile maps have been shown to support wayfinding in real-world environments. Some studies show that PWBs, especially early PWBs experience somewhat more difficulties than sighted persons. Considering route and layout knowledge, this was the case when tasks or tactile maps were more complex, and for location and distance representations this is the case when mental rotation was required. Nevertheless, the somewhat larger set of studies in this modality compared to the auditory modality also brings about a larger variety in study designs and methods to externalise cognitive maps. This might make it difficult to compare data, and may result in some (seemingly) ambiguous or contradictory findings.

2.4. *Cognitive maps based on information from multiple sensory modalities*

Cognitive map literature not only investigated abilities based on auditory and haptic sensory modalities only. Researchers have also combined sensory modalities, which is somewhat closer to real life navigation. Literature generally indicates that persons with blindness (PWBs) are capable of constructing cognitive maps from multimodal spatial information. Multimodal information might even be more useful than from one modality only, since they have led to more effective cognitive map construction than information from one modality only (Brayda et al., 2019; Delogu et al., 2010; Ducasse et al., 2018; Grussenmeyer et al., 2016; Papadopoulos and Barouti, 2015; Papadopoulos et al., 2017; Simonnet et al., 2012; Yatani et al., 2012). The combination of all senses most likely would lead to better spatial knowledge than information from fewer senses (Papadopoulos et al., 2017b). Several studies have implicated audio-tactile maps to assess representations of routes, general map layout, and distance between locations. Additionally, audio-tactile maps have been compared and combined with real-world navigation.

2.4.1. *Route*

PWBs were able to construct precise mental route representation after exploring an environment using a audio-haptic device (Yatani et al., 2012). Moreover, learning a route using a tactile map in combination with direct navigation is suggested to be more efficient than navigation only (Espinosa and Ochaita, 1998). Nevertheless, during navigation, simultaneous verbal instructions seem to be distracting rather than supporting (Espinosa and Ochaita, 1998).

2.4.2. *Layout*

Sighted persons, early PWBs and late PWBs formed equally accurate cognitive maps of general layout after navigating a virtual and real environment using a haptic and auditory sensory substitution device (Chebat et al., 2015), and of the layout of a audio-haptic map (Palani et al., 2022). It is therefore suggested that impaired navigation abilities in PWBs are not due to incapabilities in processing, but because of unavailability of sufficient spatial information (Chebat et al., 2015). Furthermore, mental spatial representations of PWBs were even more detailed after exploring a map or virtual environment with auditory and haptic feedback compared to direct experience of the real environment (Espinosa and Ochaita, 1998; Lahav and Mioduser, 2005, 2008a, 2008b; Lahav et al., 2018; Papadopoulos et al., 2017b).

2.4.3. *Locations*

Regarding specific locations, PWBs were able to construct precise representations of landmarks after learning an audio-tactile map (Brock and Jouffrais, 2015; Brock et al., 2015) or after exploring an environment using an audio-haptic device (Yatani et al., 2012). Nevertheless, auditory descriptions in addition to haptic information could also lead to less accurate representations due to sensory overload (Yatani et al., 2012).

2.4.4. *Distance*

After exploring landmarks in a VR environment with sound by physically walking, early and late PWBs built up a representation of distances between the landmarks. Sighted persons, however, did not (Afonso et al., 2010).

2.4.5. *Direction*

PWBs and sighted persons formed equal and accurate mental representations of distances between landmarks on an audio-haptic map (Palani et al., 2022). These representations were similar after exploring a map that is solely presented in the haptic domain (Palani et al., 2022).

2.4.6. *Support real-world navigation*

Familiarising people with an environment in a virtual environment or with a multimodal map has been proven effective in supporting navigation in the real environment. For instance, when PWBs had to perform tasks in a real world space, people were more efficient when they had first explored a virtual version of the environment compared to participants who had not (Ducasse et al., 2018; Lahav and Mioduser, 2005). This also suggests the construction of more effective, allocentric, cognitive maps after exploring a virtual space first. Knowledge from these cognitive maps, such as specific location representations, could moreover be transferred to the real world (Giudice et al., 2020; Lahav and Mioduser, 2005, 2008a; Papadopoulos et al., 2017b; Patel and Vij, 2012).

Taken together, PWBs form accurate representations of routes, general layout, distances and directions between landmarks based on the combined haptic and auditory modalities. It may even be more effective than one modality alone. Furthermore, familiarising someone with an audio-tactile map first, improves navigation in the real-world environment. Nevertheless, the number of studies about audio-tactile maps is somewhat limited, and not all types of spatial information have been addressed.

2.5. *Cognitive map formation through real-world navigation*

Apart from cognitive map formation based on models, maps and virtual environments, we reviewed literature regarding real-world navigation. Overall, literature suggests that PWBs perform equally or slightly better than sighted persons on real-world navigation tasks (Gagnon et al., 2010; Passini et al., 1990a, 1990b). Such tasks included learning new routes, combining and retracing routes, making shortcuts, pointing to locations, and reproducing the layout of the maze (Passini et al., 1990a, 1990b).

2.5.1. *Route*

Early and late PWBs made fewer errors during complex route learning than sighted persons, suggesting faster construction of route representation in PWBs (Fortin et al., 2008). When subsequently having to retrace the routes or find shortcuts, PWBs and sighted persons performed equally well (Loomis et al., 1993; Passini and Proulx, 1988). Both groups, however, seemed to encounter difficulties, suggesting that proprioceptive information alone was not sufficient for constructing flexible representations of routes (Loomis et al., 1993).

2.5.2. *Layout*

After learning routes in a real-world maze, PWBs performed slightly better than sighted persons on judgments of maze layout (Fortin et al., 2008). This suggests that PWBs could combine routes into a representation of general environmental layout.

2.5.3. *Locations*

In addition, PWBs and sighted persons improved equally well on object localisation tasks after walking from object to object (Patel and Vij, 2012). This suggests implication of locations into a cognitive map by PWBs as well as sighted persons after exploring a real environment. Early PWBs, however, have also been shown to form less accurate allocentric representations of haptic objects in a large-scale environment compared to sighted persons (Iachini et al., 2014).

2.5.4. *Distance*

Considering distances between locations, PWBs as well as sighted persons seem to construct accurate representations. PWBs showed somewhat more difficulties, however, several studies also showed equal performance in PWBs and sighted persons. For instance, after exploring objects in a large-scale environment, or experiencing multisegment routes, early PWBs, late PWBs and sighted persons seemed to build up equally accurate representations of distances between specific locations (Loomis et al., 1993; Passini and Proulx, 1988; Thinus-Blanc and Gaunet, 1997). In general, in large-scale spaces, short distances were overestimated, and long distances were underestimated (Loomis et al., 2001). Early PWBs have shown compressed representations of locomotor space, compared to late PWBs and sighted persons (Gori et al., 2017). PWBs have also been reported to perform worse than sighted persons on distance estimation tasks (Gagnon et al., 2010; Gaunet and Thinus-Blanc, 1996; Legge et al., 2016). This might be due to higher capabilities of sighted persons to shift from egocentric to allocentric strategies (Gagnon et al., 2010). Basic perceptual processing did not seem to be impaired in early PWBs, but higher level processing of spatial information, such as inference of distances, might have been (Gaunet and Thinus-Blanc, 1996).

2.5.5. *Direction*

Most literature reports equal incorporation of directions into a cognitive map by PWBs and sighted persons. When estimating the direction from start- to endpoint after walking a simple three-segment route, however, PWBs performed slightly worse than sighted persons (Legge et al., 2016). Nonetheless, after learning more complex, multisegment routes or object locations in a large-scale environment, PWBs and sighted persons performed equally well when they had to estimate directions between explored locations (Fortin et al., 2008; Loomis et al., 1993; Pasqualotto et al., 2013; Passini and Proulx, 1988; Thinus-Blanc and Gaunet, 1997; Tinti et al., 2006).

Taken together, PWBs form equal or sometimes even better representations of routes, layout and specific locations than sighted persons after exploring a real-world environment. Considering distances and directions, however, results are inconsistent in showing whether PWBs form more or less accurate representations of real-world or large-scale environments than sighted persons. PWBs have been suggested to perform worse than sighted persons when tasks require inference of information from a cognitive map rather than mere memory of (proprioceptive) information, which might be applicable to estimation of distances and directions (Klatzky et al., 1995). Furthermore, it has been suggested that differences between PWBs and sighted persons were not due to visual impairments per se, but rather due to limited availability of spatial information or differences in navigational strategies used to solve spatial tasks (Thinus-Blanc and Gaunet, 1997; Ungar, 2000). (Table 2).

2.6. *Role of navigation strategies in cognitive map formation*

Whether someone can form a route or survey representation of an environment, and whether someone uses a route or survey strategy during navigation or spatial tasks seems to affect their navigational abilities (Prestopnik and Roskos-Ewoldsen, 2000). Being able to construct survey representations or use an allocentric perspective is not required for successful navigation. Nevertheless, it facilitates wayfinding, as allocentric or survey strategies are suggested to be more effective in learning routes than egocentric or route strategies (Gagnon et al., 2010). Route representations or egocentric perspectives are sufficient for simple spatial tasks, but performance on more complex tasks improves when a survey representation is used (Gagnon et al., 2010; Lederman et al., 1985; Papadopoulos et al., 2012). Some tasks require a route representation, others a survey representation or strategy. The ability to switch between the two, depending on the demands, might be important to complete complex navigational tasks (Gagnon et al., 2010; Gaunet and Rossetti, 2006; Kupers et al., 2010). Many studies have implicated the effects of using route and survey strategies on cognitive maps formation in persons with blindness (PWBs). Generally, there are three trends in literature. Some argue that PWBs rely solely on route representations, because non-visual modalities are egocentric. Other research indicates that PWBs are able to form survey representations but that they often experience difficulties. The third trend in literature even suggests that PWBs form equal or better survey representations than sighted persons, when the required spatial information is available.

2.6.1. *Persons with blindness rely on route representations*

Many studies argue that PWBs, and mainly early PWBs, rely on route representations (Cattaneo et al., 2008; Corazzini et al., 2010; Cornoldi et al., 2009; Gori et al., 2017; Iachini et al., 2014; Lederman et al., 1985; Pasqualotto and Proulx, 2012; Thinus-Blanc and Gaunet, 1997). Non-visual modalities are mainly egocentric (Millar, 1988, 1994; Schmidt et al., 2013), and because PWBs have limited access to distal cues, they might rely on egocentric cues (Millar, 1988, 1994; Thinus-Blanc and Gaunet, 1997). Moreover, during locomotion, the body position is an unstable reference, only allowing for building a representation of a route (Thinus-Blanc and Gaunet, 1997). Along the same lines, haptic and auditory cues are less suitable to convey parallel information (Pasqualotto and Proulx, 2012). Furthermore, a survey representation requires multisensory integration, which is in turn promoted by (early) visual experience. This suggests that especially early PWBs perform worse than sighted persons on spatial tasks where a survey representation is required, but equal or even better when a route representation is sufficient (Pasqualotto and Proulx, 2012; Thinus-Blanc and Gaunet, 1997).

Also other studies show that PWBs mostly form route representations, and have difficulties using survey representations. For example, PWBs generally overestimated short distances, but underestimated long distances. This indicates the formation of a route representation, however, sighted persons seemed to additionally construct survey representations (Gori et al., 2017; Lederman et al., 1985). Besides, PWBs were less proficient in acquiring, inferring and using spatial knowledge based on survey information compared to route information, such as routes, locations and distances (Corazzini et al., 2010; Cornoldi et al., 2009; Iachini et al., 2014; Noordzij et al., 2006), especially in large-scale spaces (Iachini et al., 2014). Sighted persons, however, constructed spatial representations based on both survey and route information in these studies.

Overall, this research suggest that visual experience is required to develop abilities for constructing survey representations and using survey-like information. The results indicate that vision is necessary to integrate spatio-temporal information into a survey representation (Iachini et al., 2014).

Table 2
Summary of results for each information type, tested in each modality.

	Auditory	Haptic	Multiple modalities	Real-world navigation
Route	Persons with blindness (PWBs) form representation*	PWBs and sighted persons form equal representation, but accuracy of representations in PWBs lower than in sighted persons on complex tasks or routes	PWBs form representation*	PWBs form more accurate representation than sighted persons
Layout	PWBs form representation, but less accurate than sighted persons	PWBs and sighted persons form equal representation, but accuracy of representations in PWBs lower than in sighted persons on complex tasks or map layouts	PWBs and sighted persons form equal representation	PWBs form more accurate representation than sighted persons
Locations	PWBs and sighted persons form equal representation	PWBs and sighted persons form equal representation, but accuracy of representations in early PWBs lower than late PWBs and sighted persons when mental rotation is required	PWBs form representation*	PWBs and sighted persons form equal representation
Distance	Early PWBs form less accurate representation than late PWBs and sighted persons	Accuracy of representations in early PWBs lower than late PWBs and sighted persons when mental rotation is required	PWBs form more accurate representation than sighted persons	PWBs sometimes form equal, sometimes less accurate representations as sighted persons
Direction	#	Early PWBs form slightly less accurate representation than late PWBs and sighted persons	PWBs and sighted persons form equal representation	PWBs sometimes form equal, sometimes less accurate representations as sighted persons

*no sighted persons tested
#information type not tested in this modality

2.6.2. *Persons with blindness can form survey representations, but with more difficulty than route representations*

Several studies suggest that the lack of vision, especially in early PWBs, induces constructions of route representation, but that PWBs might nevertheless be able to generate survey representations (Cattaneo et al., 2008; Coluccia et al., 2009; Corazzini et al., 2010; Gagnon et al., 2012; Gaunet et al., 1997; Giudice, 2018; Hill et al., 1993; Millar, 1988, 1994; Noordzij et al., 2006; Papadopoulos and Koustriava, 2011; Papadopoulos et al., 2017; Papadopoulos, Koustriava, and Kartasidou, 2011; Pasqualotto et al., 2013; Passini and Proulx, 1988; Picard and Pry, 2009; Ruggiero et al., 2009, 2012; Schinazi et al., 2016; Steyvers and Kooijman, 2006; Thinus-Blanc and Gaunet, 1997; Tinti et al., 2006; Ungar, 2000). For instance, early work advocates that spatial encoding exists on the levels of movement-related information (proprioception), body-centered cues, and external cues or reference frames (Millar, 1988, 1994). Since non-visual information conveys fewer and less reliable external cues, PWBs would experience difficulties using an external reference frame (allocentric perspective). If, however, external cues become available, survey (allocentric) representations could be present in PWBs (Millar, 1988, 1994; Papadopoulos et al., 2017). Furthermore, PWBs performed better on spatial tasks when they employ a route or egocentric strategy than when they use a survey or allocentric strategy (Fortin et al., 2008; Tinti et al., 2006). Their route knowledge after exploring a small-scale tactile map was also better than survey knowledge, however, survey knowledge improved more with training (Picard and Pry, 2009). Difficulties in using survey strategies could also lead to difficulties in tasks involving mental rotation, as the cognitive load of such tasks is higher when using a route strategy (Lederman et al., 1985; Thinus-Blanc and Gaunet, 1997; Ungar, 2000). For simpler tasks that do not require spatial inference, however, route strategies would be sufficient. On such tasks, PWBs generally performed similarly to sighted persons (Klatzky et al., 1995; Millar, 1994; Thinus-Blanc and Gaunet, 1997; Ungar, 2000). Moreover, it might be possible to train PWBs on using more efficient spatial strategies (Ungar, 2000).

Several studies show that especially early PWBs experience difficulties in the construction of survey representation. For instance, early PWBs were better at inferring spatial information in egocentric compared to allocentric conditions, but it was the other way around for late PWBs and sighted persons (Pasqualotto et al., 2013; Ruggiero et al., 2012; Steyvers and Kooijman, 2006). Moreover, with a stable route or egocentric representation, early PWBs seemed to be able to overcome their difficulties in allocentric judgments on some types of spatial information (Ruggiero et al., 2012). It seems that visual experience promotes development of allocentric or survey representations (Gagnon et al., 2010; Gaunet and Rossetti, 2006; Pasqualotto et al., 2013). Mental imagery, which is facilitated by visual experience, might lead to better performance on tasks requiring a survey representation (Schmidt et al., 2013). However, the ability of early PWBs to construct survey representations is not ruled out (Gagnon et al., 2010; Gaunet and Rossetti, 2006; Pasqualotto et al., 2013; Steyvers and Kooijman, 2006). PWBs were able to build up a survey-like representation, although slower and less accurately than sighted persons (Steyvers and Kooijman, 2006).

Another factor that influences the ability to construct and use survey representations is autonomy of navigation, and how PWBs are trained (Noordzij et al., 2006; Schmidt et al., 2013). Early PWBs perform worse when they have to infer information from survey-type information than late PWBs and sighted persons. However, PWBs who travel autonomously in their daily lives perform better than persons who are not able to do so. Autonomous PWBs might encounter more situations that require a survey strategy and might therefore be more trained (Schmidt et al., 2013). Furthermore, how people experience or explore a spatial environment affects the construction of a route- or survey-type representation (Gaunet et al., 1997). Two general exploration strategies are back-and-forth, and cyclic exploration, which is experiencing for instance object locations in a sequence of visits (Gaunet et al., 1997). The former leads to more precise encoding of distances between objects and overall configuration, which induces a survey-like representation. Early PWBs employed a cyclic exploration strategy more often compared to late PWBs and sighted persons. This might have lead to a worse survey representation (Gaunet et al., 1997; Thinus-Blanc and Gaunet, 1997). Additionally, survey knowledge was better after exploring a tactile or audio-tactile map than after direct experience of the environment by walking (Espinosa and Ochaita, 1998; Papadopoulos and Barouti, 2015; Papadopoulos et al., 2017a).

2.6.3. *Persons with blindness are able to construct survey representations*

There is also literature that suggests that PWBs do not experience difficulties in constructing survey representations when the required spatial information is available (Cattaneo et al., 2008; Fortin et al., 2008; Ittyerah et al., 2007; Kupers et al., 2010; Miao et al., 2017; Palani et al., 2022; Papadopoulos et al., 2012; Tinti et al., 2006). For instance, PWBs could form flexible allocentric representations of a tactile or audio-haptic virtual environment (Kupers et al., 2010; Palani et al., 2022), and continuously switch between egocentric and allocentric strategies (Kupers et al., 2010). This might be important to complete complex navigational tasks, and can be promoted by developing autonomous navigation skills (Gagnon et al., 2010; Gaunet and Rossetti, 2006; Kupers et al., 2010; Papadopoulos et al., 2012). Exploration of audio-tactile maps also lead to similar route and survey knowledge (Brock and Jouffrais, 2015; Brock et al., 2015). In addition, it seems that the type of modality itself would not affect the acquisition of route or survey knowledge of a map by PWBs (Miao et al., 2017). PWBs sometimes performed even better on survey-type tasks like distance estimation than sighted persons (Cattaneo et al., 2008; Ittyerah et al., 2007; Tinti et al., 2006).

Taken together, all three trends find support in literature. A part of researchers believe that PWBs, especially early PWBs, rely on egocentric information and route representations. A larger portion of studies, however, argues that survey representations can be formed by PWBs, although with somewhat greater difficulty compared to sighted persons. Nevertheless, the large diversity in study designs makes it difficult to infer what exactly gives rise to the contradictory claims. Apart from visual experience, other factors may also play a role. There are most likely individual differences between PWBs in their ability to construct and use survey representations, like there are between individual sighted persons as well. For instance, PWBs who have more experience in traveling autonomously construct better survey representations than persons who hardly travel (Schmidt et al., 2013).

2.7. Discussion

In this review, we set out literature about cognitive map formation by persons with blindness and sighted persons based on auditory, haptic, and multimodal information. In these studies, representations several types of spatial information have been used as behavioural measures of cognitive map formation. These include knowledge about routes, general map layout, specific locations, estimations of distances and estimations of directions between locations. Furthermore, we explored the role of different navigational strategies on the formation of cognitive maps.

2.7.1. Cognitive map formation using auditory, haptic and multimodal information

Overall, persons with blindness as well as sighted persons can form mental representations of the spatial information types based on the non-visual sensory modalities. The accuracy, however, somewhat differs between PWBs and sighted persons for some of the behavioural measures. In the auditory modality, PWBs show good representations of route, layout and specific locations. Early PWBs, however, seem to experience somewhat more difficulties representing distances compared to late PWBs and sighted persons. In the haptic modality, PWBs and sighted persons perform equally well representing routes, layout and locations of simple environments. When the environments become more complex, routes and layouts are represented slightly worse by PWBs. Also for locations and distances, early PWBs perform less well than late PWBs and sighted persons when mental rotation is required. Early PWBs furthermore represent directions less well compared to late PWBs and sighted persons. On multimodal, audio-tactile maps, PWBs form accurate representations of routes and layout, and even more accurate ones of distances compared to sighted persons. In real-world navigation tasks, PWBs form better representations of routes and layout than sighted persons, and equal ones of locations. Considering distances and directions there are mixed results when comparing PWBs and sighted persons. Studies comparing spatial mental representations between PWBs and sighted persons sometimes seem ambiguous or contradictory. One important thing to note here, is that there is a large diversity in research designs and how cognitive maps or specific spatial information types are externalised exactly, making it difficult to compare them and possibly leading to these ambiguities.

PWBs, especially early PWBs, perform slightly worse when the environment is complex, or when mental rotation is required. In these cases, it may be that they have to infer information from their cognitive map that is not explicitly learned. Having a survey representation of the environment could be beneficial in these cases. PWBs, however may not always have enough opportunity to build up such a survey representation.

Based on all literature, we can form some speculations on how different modalities can be deployed to construct cognitive maps. For instance, audition can provide relevant information about landmarks using iconic cues or verbal descriptions (Connors et al., 2014a, 2014b; Loeliger and Stockman, 2014), and verbal descriptions of environments contribute to representations of routes and distances between relevant locations (Afonso et al., 2010; Noordzij et al., 2006; Steyvers and Kooijman, 2009). Ambient sounds can furthermore be used to build an immersive environment to safely explore the space before navigating in the real-world environment (Aziz et al., 2022; Connors et al., 2014a, 2014b; Loeliger and Stockman, 2014). Exploring such a virtual environment leads to accurate cognitive maps. Tactile maps are effective in quickly generating a map-like representation, including specific locations, and distances and directions between these locations (Jacobson and Kitchin, 1995; Papadopoulos et al., 2012; Thinus-Blanc and Gaunet, 1997). They can for instance be explored before navigating in the real environment to construct a survey-like representation in advance (Caddeo et al., 2006; Ducasse et al., 2018; Jacobson and Kitchin, 1995; Ungar, 2000), or carried during navigation to keep track of one's position along a route (Espinosa and Ochaita, 1998). The auditory and haptic modalities are hardly directly compared, possibly because of many differences in how the information is conveyed exactly (verbal descriptions or a auditory virtual environment versus a tactile map). We speculate, however, that haptic information may be more appropriate to convey small-scale map information, as haptic feedback can be easily spatially interpreted. Sound may be included to provide for instance more information about landmarks. In large-scale spaces, however, the auditory modality can substantially contribute to orientation, as the direction and approximate distance of sound sources can be detected (Després et al., 2005; Finocchietti et al., 2017). Nevertheless, a combination of sensory modalities may lead to more robust cognitive maps compared to only one modality.

Moreover, when studies report that PWBs experience difficulties in representation, they often report this regarding allocentric features (distance and directions) and survey representations. Therefore, maybe an even more important consideration that the different modalities, is the ability to use route and survey strategies in appropriate situations (see section 7.2). Early PWBs are often reported to experience more difficulties in constructing a survey representation compared to late PWBs and sighted persons, highlighting a role of visual experience. Many studies, however, also suggest that it is possible to improve survey representations up to similar level as late PWBs and sighted persons by extensive training (Gagnon et al., 2012; Miao et al., 2017; Palani et al., 2022; Picard and Pry, 2009; Ungar, 2000). This may include for instance focusing on allocentric features (i.e., focuse on spatial relationships between landmarks, instead of only on egocentric relationships), the integration of multiple (overlapping) routes into a map-like representation, exploring landmarks in various orders instead of in the same sequence, or first exploring the perimeter of an environment, followed by the space in between (Bozeman and McCulley, 2010; Gaunet et al., 1997).

Overall, PWBs as well as sighted persons can build up cognitive maps based on auditory, haptic, as well as multimodal information, although the accuracy sometime somewhat differs between PWBs and sighted persons. Information from different sensory modalities seem to be integrated into a spatial representation. The finding that combining auditory and haptic information is more effective than one modality only, even point to integration of modalities into one representation. This is in line with ideas of modality-independent coding of space in the brain. This growing body of literature points to the integration of multiple modalities into one spatial representation, instead of a separate representation for each modality (Giudice et al., 2011; Huffman and Ekstrom, 2019; Loomis et al., 2013; Palani et al., 2022; Wolbers et al., 2011).

Rodent studies have discovered the neural basis of cognitive maps, and have recorded space-related activity of for instance place cells, boundary cells and grid cells (Moser et al., 2008; O'Keefe and Burgess, 1996). Evidence for such cells has also been found in humans, using visual input (Bird et al., 2010; Doeller et al., 2010; Ekstrom et al., 2003). A limited number of studies has investigated neural activity related to spatial navigation based on non-visual information. Those studies show differential brain activation in PWBs compared to sighted persons. For instance, participants who performed well during a route navigation task in an auditory virtual environment showed activation of the temporal parietal junction, while participants who performed less well, showed more dispersed activation of early sensory and parahippocampal regions (Halko et al., 2014). Furthermore, during tactile environment exploration, PWBs and sighted persons both activate regions related to visuo-spatial processing, which is according to cognitive map construction (Campus et al., 2012). Hereby, PWBs also activate occipital areas. Partially differential cortical activation, however, has also been shown between PWBs and sighted persons during tactile maze solving. Hereby PWBs activate the hippocampal formation and occipital regions, while sighted persons do not, suggesting differential use of navigation strategies (Gagnon et al., 2012). In addition, larger hippocampal volume has been associated with better real-world route learning (Fortin et al., 2008). It might be interesting to further investigate the neural basis of cognitive maps based on non-visual sensory modalities. Because non-visual input can lead to cognitive map formation on a behavioural level, one speculation could be that spatially tuned neurons not only receive input from vision, but also from other modalities. This would be in accordance with hypotheses of modality-independent coding of space. More research, however, is required to assess this speculation.

2.7.2. Role of navigation strategies in cognitive map formation

We reviewed the literature on the role of navigational strategies in the formation of a cognitive map. Some studies claim that PWBs rely on route representations, since non-visual sensory modalities are egocentric. A larger part of literature, however, shows that PWBs are able to form survey representations when the required spatial information is available. In some studies, PWBs experience more difficulties than sighted persons, but in other literature they construct equal or even better survey representation compared to sighted persons.

We speculate that these discrepancies can be partially explained by differences in for instance methodology, variation in visual experience (early and late PWBs), and initial spatial abilities of participants. For instance, results suggesting that PWBs rely on route representations and form worse survey representations compared to sighted persons are often based on complex routes or maps (e.g., Cornoldi et al., 2009; Gagnon et al., 2010; Lederman et al., 1985; Noordzij et al., 2006; Passini and Proulx, 1988), whereas studies suggesting that PWBs can form survey representations mostly involve simple to moderately complex routes or maps (e.g., Brock et al., 2015; Fortin et al., 2008; Miao et al., 2017; Palani et al., 2022; Papadopoulos et al., 2017; Picard and Pry, 2009; Tinti et al., 2006). Few studies report better performance by late PWBs compared to sighted persons on survey tasks (Ittyerah et al., 2007; Tinti et al., 2006). We speculate that this may have arisen because PWBs are more used to incorporating haptic information than sighted, and they might additionally benefit from their visual experience. Several studies furthermore suggest that autonomous navigation abilities of PWBs are related to better survey representations (e.g., Papadopoulos et al., 2012; Schmidt et al., 2013; Steyvers and Kooijman, 2006; Tinti et al., 2006), nevertheless, the causal link is unclear in this aspect, and not all studies report general navigation abilities of participants. Moreover, we speculate that visual experience is an important factor in the competence to construct survey representations. Across literature, when worse survey knowledge is reported, this mostly concerns early PWBs, while late PWBs often perform similarly to sighted persons (e.g., Corazzini et al., 2010; Cornoldi et al., 2009; Gagnon et al., 2010; Iachini et al., 2014; Passini and Proulx, 1988; Schmidt et al., 2013). Early PWBs often perform worse when survey knowledge is required, such as in tasks where mental rotation is necessary (Coluccia et al., 2009; Papadopoulos et al., 2011). Late PWBs and sighted persons may have an advantage in forming mental representations of an environment, because visual experience promotes spatial imagery abilities, which in turn advances abilities such as mental rotation (Cornoldi et al., 2009; Gaunet et al., 1997; Pasqualotto and Proulx, 2012; Thinus-Blanc and Gaunet, 1997). Most literature, however, indicates that also early PWBs can form survey representations. Even studies suggesting that these individuals rely on egocentric information, do not rule out the presence or the ability to acquire any survey knowledge (Corazzini et al., 2010; Iachini et al., 2014; Lederman et al., 1985; Millar, 1988; Schmidt et al., 2013). One consideration here is that studies sometimes only report group differences, but not whether the groups separately perform well. It might be the case that early PWBs did form survey representations, but that only their worse performance compared to late PWBs and sighted participants, or compared to their route representation, was reported.

Taking all literature together, we speculate that PWBs without visual experience (early PWBs) actually experience more difficulties in the formation of survey representations, but that this improves when they are trained or when sufficient survey information is easily available to these individuals. Non-visual information is actually mostly egocentric, but it can be provided in a way that a person can use it to construct a survey representation (Millar, 1988; Schmidt et al., 2013). Moreover, multiple studies suggest that people can be trained in acquiring survey knowledge (e.g., Cornoldi et al., 2009; Gagnon et al., 2012; Gaunet et al., 1997; Palani et al., 2022; Ungar, 2000). Early PWBs sometimes rely on a verbal strategy, which is remembering a spatial description rather than forming a spatial representation (Chiesa et al., 2017; Cornoldi et al., 2009). This is a sign of not knowing how to construct one or of not being properly trained. They then seem to compensate on a perceptual level (Cornoldi et al., 2009). Furthermore, PWBs who travel autonomously in daily lives, are able to construct better survey representations than persons who hardly travel autonomously (e.g., Papadopoulos et al., 2012; Schmidt et al., 2013; Steyvers and Kooijman, 2006; Tinti et al., 2006). This could point to an effect of training.

Another important consideration, is that survey representations are not necessarily superior to route representations (Millar, 1988). This depends on the specific situation or issue that has to be resolved. Furthermore, it could be the case that it is the ability to switch between strategies rather than the formation of route or survey representations per se that contributes to spatial cognition (Gagnon et al., 2010; Gaunet and Rossetti, 2006; Kupers et al., 2010). Therefore, PWBs may not necessarily have a disadvantage, even when they mainly rely on route representations (Millar, 1988).

3. Conclusions

Taking all results together, persons with blindness as well as sighted persons can build up cognitive maps based on auditory, haptic, as well as multimodal information. Although the auditory and haptic modalities have not been directly compared, we speculate that they partially vary in what kind of spatial information they most effectively convey. In addition, combining multiple modalities may contribute to a more robust cognitive map compared to only one modality.

Cognitive map accuracy sometimes differs between PWBs and sighted persons. We speculate that discrepancies partially arise because early PWBs experience somewhat more difficulties in constructing a survey representation, and not all studies distinguish between early and late PWBs. Additionally, differences in specific methodology may give rise to some inconsistencies. PWBs as well as sighted persons seem to be able to construct route as well as survey representations, however, especially early PWBs build up slightly less accurate survey representations. Nevertheless, many studies suggests that these individuals can acquire this ability with sufficient spatial information or training.

Declarations of interest

None.

Acknowledgements

This work was supported by ZonMw InZicht (grant 94312004).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2022.104797.

References

Afonso, A., Blum, A., Katz, B.F.G., Tarroux, P., Borst, G., Denis, M., 2010. Structural properties of spatial representations in blind people: Scanning images constructed from haptic exploration or from locomotion in a 3-D audio virtual environment. Mem. Cogn. 38 (5), 591–604. https://doi.org/10.3758/MC.38.5.591.

Aziz, N., Stockman, T., Stewart, R., 2022. Planning your journey in audio: design and evaluation of auditory route overviews. ACM Trans. Access. Comput. https://doi.org/10.1145/3531529.

Bird, C.M., Capponi, C., King, J.A., Doeller, C.F., Burgess, N., 2010. Establishing the boundaries: the hippocampal contribution to imagining scenes. J. Neurosci. 30 (35), 11688–11695. https://doi.org/10.1523/JNEUROSCI.0723-10.2010.

Blades, M., Lippa, Y., Golledge, R.G., Jacobson, R.D., Kitchin, R.M., 2002. The effect of spatial tasks on visually impaired peoples' wayfinding abilities. J. Vis. Impair. Blind. 96 (6), 407–419. https://doi.org/10.1177/0145482x0209600604.

Blanco, F., Travieso, D., 2003. Haptic exploration and mental estimation of distances on a fictitious island: from mind's eye to mind's hand. J. OfVisual Impair. Blind. May 2003, 298–300.

Bozeman, L., McCulley, R.M., 2010. Improving orientation for students with vision loss. In: Wiener, W.R., Welsh, R.L., Blasch, B.B. (Eds.), Foundations of Orientation and Mobility. Volume II: Instructional Strategies and Practical Applications. AFB Press, American Foundation for the Blind, New York, USA, pp. 27–53.

Brambring, M., 1976. The structure of haptic space in the blind and sighted. Psychol. Res. 38 (3), 283–302. https://doi.org/10.1007/BF00309777.

Brayda, L., Leo, F., Baccelliere, C., Vigini, C., Cocchi, E., 2019. A refreshable tactile display effectively supports cognitive mapping followed by orientation and mobility tasks. Proceedings of the 2nd Workshop on Multimedia for Accessible Human Computer Interfaces - MAHCI '19. ACM Press,, New York, New York, USA, pp. 9–15. https://doi.org/10.1145/3347319.3356840.

Brock, A., Jouffrais, C., 2015. Interactive audio-tactile maps for visually impaired people. SIGACCESS (113)).

Brock, A., Truillet, P., Oriola, B., Picard, D., Jouffrais, C., 2015. Interactivity improves usability of geographic maps for visually impaired people. Hum. -Comput. Interact. 30 (2), 156–194. https://doi.org/10.1080/07370024.2014.924412.

Burgess, N., Maguire, E.A., O'Keefe, J., 2002. The human hippocampus and spatial and episodic memory. Neuron 35 (4), 625–641. https://doi.org/10.1016/S0896-6273(02)00830-9.

Caddeo, P., Fornara, F., Nenci, A.M., Piroddi, A., 2006. Wayfinding tasks in visually impaired people: the role of tactile maps. Cogn. Process. 7 (SUPPL. 1), 168–169. https://doi.org/10.1007/s10339-006-0128-9.

Campus, C., Brayda, L., De Carli, F., Chellali, R., Famà, F., Bruzzo, C., Rodriguez, G., 2012. Tactile exploration of virtual objects for blind and sighted people: the role of beta 1 EEG band in sensory substitution and supramodal mental mapping. J. Neurophysiol. 107 (10), 2713–2729. https://doi.org/10.1152/jn.00624.2011.

Cattaneo, Z., Vecchi, T., Cornoldi, C., Mammarella, I., Bonino, D., Ricciardi, E., Pietrini, P., 2008. Imagery and spatial processes in blindness and visual impairment. Neurosci. Biobehav. Rev. 32 (8), 1346–1360. https://doi.org/10.1016/j.neubiorev.2008.05.002.

Chebat, D.-R., Maidenbaum, S., Amedi, A., 2015. Navigation using sensory substitution in real and virtual mazes. PLoS ONE 10 (6), e0126307. https://doi.org/10.1371/journal.pone.0126307.

Chiesa, S., Schmidt, S., Tinti, C., Cornoldi, C., 2017. Allocentric and contra-aligned spatial representations of a town environment in blind people. Acta Psychol. 180, 8–15. https://doi.org/10.1016/j.actpsy.2017.08.001.

Cobo, A., Guerrón, N.E., Martín, C., del Pozo, F., Serrano, J.J., 2017. Differences between blind people's cognitive maps after proximity and distant exploration of virtual environments. Comput. Hum. Behav. 77, 294–308. https://doi.org/10.1016/j.chb.2017.09.007.

Coluccia, E., Mammarella, I., Cornoldi, C., 2009. Centred egocentric, decentred egocentric, and allocentric spatial representations in the peripersonal space of congenital total blindness. Perception 38 (5), 679–693.

Connors, E.C., Chrastil, E.R., Sánchez, J., Merabet, L.B., 2014a. Action video game play and transfer of navigation and spatial cognition skills in adolescents who are blind. Front. Hum. Neurosci. 8, 133. https://doi.org/10.3389/fnhum.2014.00133.

Connors, E.C., Chrastil, E.R., Sánchez, J., Merabet, L.B., 2014b. Virtual environments for the transfer of navigation skills in the blind: a comparison of directed instruction vs. video game based learning approaches. Front. Hum. Neurosci. 8, 223. https://doi.org/10.3389/fnhum.2014.00223.

Corazzini, L.L., Tinti, C., Schmidt, S., Mirandola, C., Cornoldi, C., 2010. Developing spatial knowledge in the absence of vision: allocentric and egocentric representations generated by blind people when supported by auditory cues. Psychol. Belg. 50 (3–4), 327–334. https://doi.org/10.5334/pb-50-3-4-327.

Cornoldi, C., Tinti, C., Mammarella, I.C., Re, A.M., Varotto, D., 2009. Memory for an imagined pathway and strategy effects in sighted and in totally congenitally blind individuals. Acta Psychol. 130 (1), 11–16. https://doi.org/10.1016/j.actpsy.2008.09.012.

Delogu, F., Palmiero, M., Federici, S., Plaisant, C., Zhao, H., Belardinelli, O., 2010. Non-visual exploration of geographic maps: does sonification help? Disabil. Rehabil.: Assist. Technol. 5 (3), 164–174. https://doi.org/10.3109/17483100903100277.

Després, O., Boudard, D., Candas, V., Dufour, A., 2005. Enhanced self-localization by auditory cues in blind humans. Disabil. Rehabil. 27 (13), 753–759. https://doi.org/10.1080/09638280400014865.

Deuker, L., Bellmund, J.L.S., Navarro Schröder, T., Doeller, C.F., 2016. An event map of memory space in the hippocampus. ELife 5, e16534. https://doi.org/10.7554/eLife.16534.

Doeller, C.F., Barry, C., Burgess, N., 2010. Evidence for grid cells in a human memory network. Nature 463 (7281), 657–661. https://doi.org/10.1038/nature08704.

Ducasse, J., Brock, A., Jouffrais, C., 2018. Accessible interactive maps for visually impaired users. In: Pissaloux, E., Velázquez, R. (Eds.), Mobility of Visually Impaired People: Fundamentals and ICT Assistive Technologies. Springer, pp. 537–584. https://doi.org/10.1007/978-3-319-54446-5.

Eichenbaum, H., Dudchenko, P., Wood, E., Shapiro, M., Tanila, H., 1999. The hippocampus, memory, and place cells: is it spatial memory or a memory space? Neuron 23 (2), 209–226. https://doi.org/10.1016/S0896-6273(00)80773-4.

Ekstrom, A.D., Kahana, M.J., Caplan, J.B., Fields, T.A., Isham, E.A., Newman, E.L., Fried, I., 2003. Cellular networks underlying human spatial navigation. Nature 425 (6954), 184–188. https://doi.org/10.1038/nature01955.1.

Epstein, R.A., Patai, E.Z., Julian, J.B., Spiers, H.J., 2017. The cognitive map in humans: spatial navigation and beyond. Nat. Neurosci. 20 (11), 1504–1513. https://doi.org/10.1038/nn.4656.

Espinosa, M.A., Ochaita, E., 1998. Using tactile maps to improve the practical spatial knowledge of adults who are blind. J. Vis. Impair. Blind. 92 (5), 338–345 (Retrieved from). 〈https://www.afb.org/afbpress/newpubjvib.asp?DocID=jvib920511〉.

Finocchietti, S., Cappagli, G., Gori, M., 2017. Auditory spatial recalibration in congenital blind individuals (vol 11, 76, 2017). Front. Neurosci. 11 https://doi.org/10.3389/fnins.2017.00268.

Foo, P., Warren, W.H., Duchon, A., Tarr, M.J., 2005. Do humans integrate routes into a cognitive map? Map- versus landmark-based navigation of novel shortcuts. J. Exp. Psychol. Learn., Mem., Cogn. 31 (2), 195–215. https://doi.org/10.1037/0278-7393.31.2.195.

Fortin, M., Voss, P., Rainville, C., Lassonde, M., Lepore, F., 2006. Impact of vision on the development of topographical orientation abilities. NeuroReport 17 (4), 443–446. https://doi.org/10.1097/01.wnr.0000203626.47824.86.

Fortin, M., Voss, P., Lord, C., Lassonde, M., Pruessner, J., Saint-Amour, D., Lepore, F., 2008. Wayfinding in the blind: larger hippocampal volume and supranormal spatial navigation. Brain 131 (11), 2995–3005. https://doi.org/10.1093/brain/awn250.

Gagnon, L., Kupers, R., Schneider, F.C., Ptito, M., 2010. Tactile maze solving in congenitally blind individuals. NeuroReport 21 (15), 1. https://doi.org/10.1097/WNR.0b013e32833eaaf9.

Gagnon, L., Schneider, F.C., Siebner, H.R., Paulson, O.B., Kupers, R., Ptito, M., 2012. Activation of the hippocampal complex during tactile maze solving in congenitally blind subjects. Neuropsychologia 50 (7), 1663–1671. https://doi.org/10.1016/j.neuropsychologia.2012.03.022.

Gaunet, F., Rossetti, Y., 2006. Effects of visual deprivation on space representation: immediate and delayed pointing toward memorized proprioceptive targets. Perception 35, 107–124.

Gaunet, F., Thinus-Blanc, C., 1996. Early-blind subjects' spatial abilities in the locomotor space: exploratory strategies and reaction-to-change performance. Perception 25 (8), 967–981. https://doi.org/10.1068/p250967.

Gaunet, F., Martinez, J.-L., Thinus-Blanc, C., 1997. Early-blind subjects' spatial representation of manipulatory space: exploratory strategies and reaction to change. Perception 26 (3), 345–366. https://doi.org/10.1068/p260345.

Giudice, N.A., Betty, M.R., Loomis, J.M., 2011. Functional equivalence of spatial images from touch and vision: evidence from spatial updating in blind and sighted individuals. J. Exp. Psychol. -Learn. Mem. Cogn. 37 (3), 621–634. https://doi.org/10.1037/a0022331.

Giudice, N.A., Guenther, B.A., Jensen, N.A., Haase, K.N., 2020. Cognitive mapping without vision: comparing wayfinding performance after learning from digital touchscreen-based multimodal maps vs. embossed tactile overlays. Front. Hum. Neurosci. 14. https://doi.org/10.3389/fnhum.2020.00087.

Giudice, N.A. (2018). Navigating without vision: principles of blind spatial cognition. In D.R. Montello (Ed.), HANDBOOK OF BEHAVIORAL AND COGNITIVE GEOGRAPHY (pp. 260–288).

Gori, M., Cappagli, G., Baud-Bovy, G., Finocchietti, S., 2017. Shape perception and navigation in blind adults. Front. Psychol. 8, 10. https://doi.org/10.3389/fpsyg.2017.00010.

Grieves, R.M., Jeffery, K.J., 2017. The representation of space in the brain. Behav. Process. 135, 113–131. https://doi.org/10.1016/j.beproc.2016.12.012.

Grussenmeyer, W., Garcia, J., Jiang, F., 2016. Feasibility of using haptic directions through maps with a tablet and smart watch for people who are blind and visually impaired. Proc. 18th Int. Conf. Hum. Comput. Interact. Mob. Devices Serv., Mob. 2016, 83–89. https://doi.org/10.1145/2935334.2935367.

Guerreiro, J., Ahmetovic, D., Kitani, K.M., Asakawa, C., 2017. Virtual navigation for blind people. ASSETS'17 Proceedings of the 19th International ACM SIGACCESS Conference on Computers and Accessibility. ACM Press, New York, New York, USA, pp. 280–289. https://doi.org/10.1145/3132525.3132545.

Hafting, T., Fyhn, M., Molden, S., Moser, M.-B., Moser, E.I., 2005. Microstructure of a spatial map in the entorhinal cortex. Nature 436, 801–806.

Halko, M.A., Connors, E.C., Sánchez, J., Merabet, L.B., 2014. Real world navigation independence in the early blind correlates with differential brain activity associated with virtual navigation. Hum. Brain Mapp. 35 (6), 2768–2778. https://doi.org/10.1002/hbm.22365.

Hill, E.W., Rieser, J.J., Hill, M.M., Hill, M., Halpin, J., Halpin, R., 1993. How persons with visual impairments explore novel spaces: strategies of good and poor performers. J. Vis. Impair. Blind. 87, 295–301.

Hollins, M., Kelley, E.K., 1988. Spatial updating in blind and sighted people. Percept. Psychophys. 43 (4), 380–388. https://doi.org/10.3758/BF03208809.

Howard, L.R., Javadi, A.H., Yu, Y., Mill, R.D., Morrison, L.C., Knight, R., Spiers, H.J., 2014. The hippocampus and entorhinal cortex encode the path and euclidean distances to goals during navigation. Curr. Biol. 24 (12), 1331–1340. https://doi.org/10.1016/j.cub.2014.05.001.

Huffman, D.J., Ekstrom, A.D., 2019. A modality-independent network underlies the retrieval of large-scale spatial environments in the human brain. Neuron 104 (3), 611–622. https://doi.org/10.1016/j.neuron.2019.08.012.

Iachini, T., Ruggiero, G., Ruotolo, F., 2014. Does blindness affect egocentric and allocentric frames of reference in small and large scale spaces? Behav. Brain Res. 273, 73–81. https://doi.org/10.1016/j.bbr.2014.07.032.

Ittyerah, M., Gaunet, F., Rossetti, Y., 2007. Pointing with the left and right hands in congenitally blind children. Brain Cogn. 64, 170–183.

Jacobson, R.D., 1998. Cognitive mapping without sight: four preliminary studies of spatial learning. J. Environ. Psychol. 18 (3), 289–305. https://doi.org/10.1006/jevp.1998.0098.

Jacobson, R.D., Kitchin, R.M., 1995. Assessing the configurational knowledge of people with visual impairments or blindness. Swans. Geogr. 32, 14–24 (Retrieved from). ⟨http://mural.maynoothuniversity.ie/7250/⟩.

Kim, M., Maguire, E.A., 2019. Encoding of 3D head direction information in the human brain. Hippocampus 29 (7), 619–629. https://doi.org/10.1002/hipo.23060.

Klatzky, R.L., 1998. Allocentric and egocentric spatial representations: definitions, distinctions, and interconnections. In: Freksa, C., Habel, C., Wender, K.F. (Eds.), Spatial Cognition: An Interdisciplinary Approach to Representing and Processing Spatial Knowledge. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–17. https://doi.org/10.1007/3-540-69342-4_1.

Klatzky, R.L., Golledge, R.G., Loomis, J.M., Cicinelli, J.G., Pellegrino, J.W., 1995. Performance of blind and sighted persons on spatial tasks. J. Vis. Impair. Blind. 1995, 70–82.

Kupers, R., Chebat, D.R., Madsen, K.H., Paulson, O.B., Ptito, M., 2010. Neural correlates of virtual route recognition in congenital blindness. Proc. Natl. Acad. Sci. 107 (28), 12716–12721. https://doi.org/10.1073/pnas.1006199107.

Lahav, O., Mioduser, D., 2005. Blind persons' acquisition of spatial cognitive mapping and orientation skills supported by virtual environment. Proc. 5th Int. Conf. Disabil., Virtual Real. Assoc. Technol. 131–138. https://doi.org/10.1515/IJDHD.2005.4.3.231.

Lahav, O., Mioduser, D., 2008a. Construction of cognitive maps of unknown spaces using a multi-sensory virtual environment for people who are blind. Comput. Hum. Behav. 24 (3), 1139–1155. https://doi.org/10.1016/j.chb.2007.04.003.

Lahav, O., Mioduser, D., 2008b. Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. Int. J. Hum. -Comput. Stud. 66 (1), 23–35. https://doi.org/10.1016/j.ijhcs.2007.08.001.

Lahav, O., Gedalevitz, H., Battersby, S., Brown, D., Evett, L., Merritt, P., 2018. Virtual environment navigation with look-around mode to explore new real spaces by people who are blind. Disabil. Rehabil. 40 (9), 1072–1084. https://doi.org/10.1080/09638288.2017.1286391.

Lederman, S.J., Klatzky, R.L., Barber, P.O., 1985. Spatial and movement-based heuristics for encoding pattern information through touch. J. Exp. Psychol.: Gen. 114 (1), 33–49 (Retrieved from). ⟨http://ovidsp.ovid.com/ovidweb.cgi?T=JS&CSC=Y&NEWS=N&PAGE=fulltext&D=med2&AN=3156945⟩.

Legge, G.E., Granquist, C., Baek, Y., Gage, R., 2016. Indoor spatial updating with impaired vision. Invest. Opthalmology Vis. Sci. 57 (15), 6757–6765. https://doi.org/10.1167/iovs.16-20226.

Lehtinen-Railo, S., Juurmaa, J., 1994. Effect of visual experience on locational judgement after perspective change in small-scale space. Scand. J. Psychol. 35, 175–183.

Loeliger, E., Stockman, T., 2014. Wayfinding without visual cues: evaluation of an interactive audio map system. Interact. Comput. 26 (5), 403–416. https://doi.org/10.1093/iwc/iwt042.

Loomis, J.M., Klatzky, R.L., Golledge, R.G., Cicinelli, J.G., Pellegrino, J.W., Fry, P.A., 1993. Nonvisual navigation by blind and sighted: assessment of path integration ability. J. Exp. Psychol.: Gen. 122 (1), 73–91 (Retrieved from). ⟨http://ovidsp.tx.ovid.com/sp-3.32.2a/ovidweb.cgi?QS2=434f4e1a73d37e8cff7fb618affc25b1c9cc918135ac9340910a097c3077a3b0f49f4823146bf2e75e8b6f27e8a42e4370753495cb320b91e5146bcf028ae65f178c0c317e584327e90e813ce9239f10ed85564843d47344d1af854c24fd00e6c7d5ec6847⟩.

Loomis, J.M., Klatzky, R.L., Golledge, R.G., 2001. Navigating without vision: basic and applied research. Optom. Vis. Sci. 78 (5), 282–289. https://doi.org/10.1097/00006324-200105000-00011.

Loomis, J.M., Klatzky, R.L., Giudice, N.A., 2013. Representing 3D space in working memory: spatial images from vision, hearing, touch, and language. In: Lacey, S., Lawson, R. (Eds.), Multisensory Imagery: Theory & Applications. Springer, pp. 131–156.

Maguire, E.A., Frackowiak, R.S.J., Frith, C.D., 1997. Recalling routes around london: activation of the right hippocampus in taxi drivers. J. Neurosci. 17 (18), 7103–7110. https://doi.org/10.1523/JNEUROSCI.17-18-07103.1997.

Maguire, E.A., Burgess, N., O'Keefe, J., 1999. Human spatial navigation: cognitive maps, sexual dimorphism, and neural substrates. Curr. Opin. Neurobiol. 9 (2), 171–177. https://doi.org/10.1016/S0959-4388(99)80023-3.

Miao, M., Zeng, L., Weber, G., 2017. Externalizing cognitive maps via map reconstruction and verbal description. Univers. Access Inf. Soc. 16 (3), 667–680. https://doi.org/10.1007/s10209-016-0497-5.

Millar, S., 1988. Models of sensory deprivation: the nature/nurture dichotomy and spatial representation in the blind. Int. J. Behav. Dev. 11 (1), 69–87. https://doi.org/10.1177/016502548801100105.

Millar, S., 1994. Understanding and representing space. Theory and Evidence from Studies with Blind and Sighted Children. Clarendon, Oxford, England.

Morgan, L.K., MacEvoy, S.P., Aguirre, G.K., Epstein, R.A., 2011. Distances between real-world locations are represented in the human hippocampus. J. Neurosci. 31 (4), 1238–1245. https://doi.org/10.1523/JNEUROSCI.4667-10.2011.

Moser, E.I., Kropff, E., Moser, M.-B., 2008. Place cells, grid cells, and the brain's spatial representation system. Annu. Rev. Neurosci. 31, 69–89. https://doi.org/10.1146/annurev.neuro.31.061307.090723.

Noordzij, M.L., Zuidhoek, S., Postma, A., 2006. The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. Cognition 100 (2), 321–342. https://doi.org/10.1016/j.cognition.2005.05.006.

O'Keefe, J., 1976. Place units in the hippocampus of the freely moving rat. Exp. Neurol. 51 (1), 78–109. https://doi.org/10.1016/0014-4886(76)90055-8.

O'Keefe, J., Burgess, N., 1996. Geometric determinants of the neurons. Nature 381, 425–428.

Palani, H.P., Fink, P.D.S., Giudice, N.A., 2022. Comparing map learning between touchscreen-based visual and haptic displays: a behavioral evaluation with blind and sighted users. Multimodal Technol. Interact. 6 (1) https://doi.org/10.3390/mti6010001.

Papadopoulos, K., Barouti, M., 2015. The contribution of audio- tactile maps to spatial knowledge of individuals with visual impairments. Proc. Int. Conf. Enabling Access Pers. Vis. Impair. (ICEAPVI-2015) 141–146.

Papadopoulos, K., Koustriava, E., 2011. The impact of vision in spatial coding. Res. Dev. Disabil. 32 (6), 2084–2091.

Papadopoulos, K., Koustriava, E., Kartasidou, L., 2011. The impact of residual vision in spatial skills of individuals with visual impairments. J. Spec. Educ. 45 (2), 118–127.

Papadopoulos, K., Koustriava, E., Kartasidou, L., 2012. Spatial coding of individuals with visual impairments. J. Spec. Educ. 46 (3), 180–190. https://doi.org/10.1177/0022466910383016.

Papadopoulos, K., Koustriava, E., Barouti, M., 2017. Cognitive maps of individuals with blindness for familiar and unfamiliar spaces: construction through audio-tactile maps and walked experience. Comput. Hum. Behav. 75, 376–384. https://doi.org/10.1016/j.chb.2017.04.057.

Papadopoulos, K., Koustriava, E., Koukourikos, P., Kartasidou, L., Barouti, M., Varveris, A., Anastasiadis, T., 2017. Comparison of three orientation and mobility aids for individuals with blindness: verbal description, audio-tactile map and audio-haptic map. Assist. Technol. 29 (1), 1–7. https://doi.org/10.1080/10400435.2016.1171809.

Pasqualotto, A., Newell, F.N., 2007. The role of visual experience on the representation and updating of novel haptic scenes. Brain Cogn. 65 (2), 184–194. https://doi.org/10.1016/j.bandc.2007.07.009.

Pasqualotto, A., Proulx, M.J., 2012. The role of visual experience for the neural basis of spatial cognition. Neurosci. Biobehav. Rev. 36 (4), 1179–1187. https://doi.org/10.1016/j.neubiorev.2012.01.008.

Pasqualotto, A., Spiller, M.J., Jansari, A.S., Proulx, M.J., 2013. Visual experience facilitates allocentric spatial representation. Behav. Brain Res. 236, 175–179. https://doi.org/10.1016/j.bbr.2012.08.042.

Passini, R., Proulx, G., 1988. Wayfinding without vision: an experiment with congenitally totally blind people. Environ. Behav. 20 (2), 227–252. https://doi.org/10.1177/0013916588202006.

Passini, R., Proulx, G., Rainville, C., 1990a. The spatio-cognitive abilities of the visually impaired population. Environ. Behav. 22 (1), 91–118. https://doi.org/10.1177/0013916590221005.

Passini, Romedi, Proulx, G., Rainville, C., 1990b. The spatio-cognitive abilities of the visually impaired population. Environ. Behav. 22 (1), 91–118. https://doi.org/10.1177/0013916590221005.

Patel, K.K., Vij, S., 2012. Spatial learning using locomotion interface to virtual environment. IEEE Trans. Learn. Technol. 5 (2), 170–176. https://doi.org/10.1109/TLT.2011.29.

Picard, D., Pry, R., 2009. Does knowledge of spatial configuration in adults with visual impairments improve with tactile exposure to a small-scale model of their urban environment? J. Vis. Impair. Blind. 103 (4), 199–209. ⟨https://www.afb.org/afbpress/newpubjvib.asp?DocID=jvib030403⟩.

Prestopnik, J.L., Roskos-Ewoldsen, B., 2000. The relations among wayfinding strategy use, sense of direction, sex, familiarity, and wayfinding ability. J. Environ. Psychol. 20 (2), 177–191. https://doi.org/10.1006/jevp.1999.0160.

Ruggiero, G., Ruotolo, F., Iachini, T., 2009. The role of vision in egocentric and allocentric spatial frames of reference. Cogn. Process. 10 (Suppl 2), S283–S285.

Ruggiero, G., Ruotolo, F., Iachini, T., 2012. Egocentric/allocentric and coordinate/categorical haptic encoding in blind people. Cogn. Process. 13, 313–317. https://doi.org/10.1007/s10339-012-0504-6.

Sánchez, J., Sáenz, M., Pascual-Leone, A., Merabet, L.B., 2010. Enhancing navigation skills through audio gaming. CHI '10 Extended Abstracts on Human Factors in Computing Systems. ACM Press, Atlanta, Georgia, USA, pp. 3991–3996. https://doi.org/10.1145/1753846.1754091.

Schinazi, V.R., Thrash, T., Chebat, D.-R., 2016. Spatial navigation by congenitally blind individuals. Wiley Interdiscip. Rev.: Cogn. Sci. 7 (1), 37–58. https://doi.org/10.1002/wcs.1375.

Schmidt, S., Tinti, C., Fantino, M., Mammarella, I.C., Cornoldi, C., 2013. Spatial representations in blind people: the role of strategies and mobility skills. Acta Psychol. 142 (1), 43–50. https://doi.org/10.1016/j.actpsy.2012.11.010.

Simonnet, M., Bothorel, C., Maximiano, L.F., Thépaut, A., Simonnet, M., Bothorel, C., Thépaut, A., 2012. GeoTablet, une application cartographique pour les personnes déficientes visuelles. Handicap, June 2012, 8–13.

Stewart, S., Jeewajee, A., Wills, T.J., Burgess, N., Lever, C., 2014. Boundary coding in the rat subiculum. Philos. Trans. R. Soc. B: Biol. Sci. 369 (1635) https://doi.org/10.1098/rstb.2012.0514.

Steyvers, F.J.J.M., Kooijman, A.C., 2006. Differences in cognitive map-acquisition between visually impaired and sighted persons. In: Pikaar, R.N., Koningsveld, E.A.P., Settels, P.J.M. (Eds.), Meeting Diversity in Ergonomics. Proceedings of the IEA 2006 congress (CD-rom, article 0398). Elsevier, Amsterdam.

Steyvers, F.J.J.M., Kooijman, A.C., 2009. Using route and survey information to generate cognitive maps: differences between normally sighted and visually impaired individuals. Appl. Cogn. Psychol. 23 (2), 223–235. https://doi.org/10.1002/acp.1447.

Thinus-Blanc, C., Gaunet, F., 1997. Representation of space in blind persons: vision as a spatial sense. Psychol. Bull. 121 (1), 20–42. https://doi.org/10.1037/0033-2909.121.1.20.

Tinti, C., Adenzato, M., Tamietto, M., Cornoldi, C., 2006. Visual experience is not necessary for efficient survey spatial cognition: evidence from blindness. Q. J. Exp. Psychol. 59 (7), 1306–1328. https://doi.org/10.1080/17470210500214275.

Ungar, S., 2000. In: Kitchin, R., Freundschuh, S. (Eds.), Cognitive Mapping without Visual Experience. Cognitive Mapping: Past, Present and Future, Routledge, London, UK, pp. 221–248 (Retrieved from). ⟨https://pdfs.semanticscholar.org/1cc6/ce0f1376ec4287583c319476a569847c6e71.pdf⟩.

Ungar, S., Blades, M., Spencer, C., 1997. Strategies for knowledge acquisition from cartographic maps by blind and visually impaired adults. Cartogr. J. 34 (2), 93–110. https://doi.org/10.1179/caj.1997.34.2.93.

Wolbers, T., Klatzky, R.L., Loomis, J.M., Wutte, M.G., Giudice, N.A., 2011. Modality-independent coding of spatial layout in the human brain. Curr. Biol. 21 (11), 984–989. https://doi.org/10.1016/j.cub.2011.04.038.

Yatani, K., Banovic, N., & Truong, K.N. (2012). SpaceSense: representing geographical information to visually impaired people using spatial tactile feedback. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (pp. 415–424). Austin, Texas, USA. https://doi.org/10.1145/2207676.2207734.

Zhong, J.Y., 2016. Relating allocentric and egocentric survey-based representations to the self-reported use of a navigation strategy of egocentric spatial updating. J. Environ. Psychol. 46, 154–175. https://doi.org/10.1016/j.jenvp.2016.04.007.