Virtual reality enabling cognitive map acquisition for persons with visual impairment: A Systematic Literature Review

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Abstract

A cognitive map (CM) is a mental model comprising information about an environment and is used to infer knowledge for spatial cognition tasks. Humans acquire a CM integrating information perceived by their senses. This makes the acquisition process different for persons with visual impairment (PVI) as they cannot easily perceive detailed information about an environment from a distance. CM can be acquired even from exploring a virtual representation of an environment. Virtual reality (VR) is a promising tool for research of CM acquisition, as it can facilitate the process, is highly customizable and allows to measure many features of the experience. This article presents a systematic literature review (SLR) of 21 recent papers focusing on VR systems which facilitate acquisition of CM for PVI. The review aims to answer four research questions aimed at mapping the current state of VR systems for PVI concerning the techniques used, the best practices identified and how are they evaluated. Suggestions for functional and non-functional requirements of new potential VR system are synthesized from the findings of the review.

1 Introduction

Like all humans, persons with visual impairment create a mental model of an environment called a cognitive map. CM contains knowledge such as locations, layout, routes, distance, and directions between locations, which can be used to infer information to support spatial tasks. Appropriate CM supports a PVI's ability to move independently, efficiently, and safely in an environment as shown by Chebat et al. (2020). CM can be acquired through direct experience of the environment, but also through indirect methods, which allow the acquisition before visiting the real environment, avoiding potential dangers associated with exploring an unknown environment. CMs acquired through a combination of indirect and direct experiences have also been observed to enable better execution of spatial tasks than CMs acquired solely through direct exploration, as indirect methods have been shown to be better suited for acquisition of allocentric (object to object) spatial knowledge by Ottink et al. (2022).

Virtual reality is one of the indirect acquisition methods, but it has not been fully explored for PVI. With increased affordability of VR technology such as head mounted displays in the recent years, more experiments aiming to create a VR system suitable for PVI are emerging. VR offers great conditions for research as it allows researchers to have complete control over an environment in which experiments are conducted, making it an attractive choice for facilitating both CM acquisition and evaluation.

While there have been reviews focusing on mapping out the state of the art of general virtual environments for PVI such as Façanha et al. (2020), there is no overview of the current situation of specifically VR for PVI. This article presents a SLR of recent papers which explored creating a VR system facilitating spatial knowledge acquisition for VIP. From initial 574 papers collected from two digital libraries, 21 papers were selected as meeting the review criteria. The article is structured in the following way: Review goals of the SLR in section 2, methodology used in the SLR in section 3, report of the results of answering research questions in section 4, limitations of the review in section 5, discussion of implications for a new potential VR system in section 6 and future work in section 7.

2 Review goals

The motivation for this literature review is to map out the current state of research of cognitive map (CM) acquisition by visually impaired persons (PVI) and virtual reality (VR) for PVI. The results will serve as one of the sources based on which a VR framework that would support CM acquisition for PVI will be designed. This paper describes a subpart of the review which focuses specifically on recent VR systems which enable acquisition of spatial information for PVI.

The review aims to answer the following research questions, which were created using the CIMO scheme. Rationales behind the questions are presented under them:

RQ1: What techniques can be used to create a VR system for PVI?
rationale: Identify the available base building blocks

for the VR framework.

RQ2: Which features of a VR system improve CM acquisition for PVI?

rationale: Identify the requirements on the VR framework so that it facilitates CM acquisition.

RQ3: To which extend are cognitive maps acquired in VR usable in the real environment?

rationale: Verify if the framework is useful for potential real life application.

RQ4: Which methods can be used to evaluate qualities of a CM for PVI?

rationale: Identify what methods to consider to use for evaluation and also if any of them could be integrated into the VR framework.

3 Review methodology

The review followed the PRISMA guideline, starting with defining the research topic and research questions presented in the previous part. Based on those a database search was conducted in the identification phase. The results from the search were further filtered in the screening phase and later judged for eligibility. The steps of the process can be seen in the workflow diagram in fig 1.

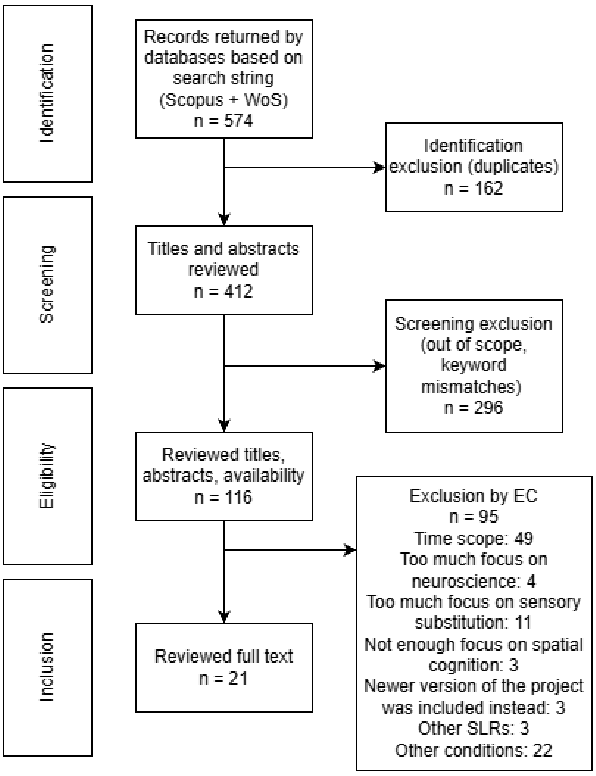

Fig. 1: SLR flow chart

3.1 Identification

The search string was created from the research topic *Supporting cognitive map acquisition among persons with vision impairments in VR*, which was divided into three blocks: 1. Cognitive map, 2. Persons with vision impairments and 3. Virtual reality. From these blocks a document-term matrix was constructed, which can be seen in table 1. This table was then used to construct the following search string:

(”cognitive map” OR ”mental map*” OR (”spatial” AND (”cognition” OR ”knowledge” OR ”learning”)) OR ”survey knowledge” OR ”route knowledge” OR ”indoor navigation” OR wayfinding OR pathfinding OR ”orientation and mobility” OR ”O&M”) AND (”visual impairment*” OR ”visual disability*” OR ”visually impaired” OR blindness OR blind) AND (”virtual reality” OR VR OR ”extended reality” OR XR OR ”augmented reality” OR AR OR ”mixed reality” OR MR)*

For the search, the following digital libraries Scopus, Web of science, SpringerLink, ACM and IEEE Xplore were considered. In the end only Scopus and Web of science were used, as the results from SpringerLink were focused too much on medicinal papers and the search string was too restrictive for ACM and IEEE Xplore.

The identification phase ended with automated duplicates removal using the Zotero software for paper cataloging, with total of 162 duplicates being removed.

3.2 LLM assisted Screening

Since Title and Abstract Screening is one of the most time-consuming parts of an SLR, a decision was made to try to automate it using large language models (LLM). With the recent rise of LLMs, there have been some research into using them for various parts of SLRs, mainly for the screening and identification phases. In their paper Joos et al. (2026) reached very promising results in Title and Abstract Screening using a consensus of multiple LLMs. Joos et al. also freely provide the software they developed for the LLM screening called LLMSurver [1], which was used for the screening. In LLM surver arbitrary LLMs connected via the OpenAI API are given a prompt describing their task of screening and they are provided with titles and abstracts of a corpus. The LLMs provide their decision of inclusion or exclusion and a short reasoning. The results then can be used to derive a final decision using a consensus scheme.

For the screening models provided by e-INFRA CZ were used as they were free and without rate limits for academic purposes. The models chosen were qwen 3.5, deepseek-v3.2-thinking, gpt-oss-120b and redhatai scout, as they were the built for reasoning and long form

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[1] https://llmsurver.dbvis.de/

Tab. 1: Document-term matrix

	Cognitive map	Persons with vision impairments	Virtual reality
Related terms	cognitive map acquisition, mental map, spatial cognition, spatial knowledge, spatial learning, survey knowledge, route knowledge	visual impairment, visually impaired, visual disability, blindness, blind	VR, virtual environment
Broader terms	indoor navigation, wayfinding, pathfinding, Orientation and Mobility, O&M	(without vision), nonvisual	Extended reality (XR), Augmented reality (AR), Mixed reality (MR)

tasks from among the other available models provided by e-INFRA CZ.

In the beginning a random sample of 20 papers was selected and manually screened. With this sample an iterative prompt and consensus scheme refinement took was done with the goal being a result that perfectly matches our own screening. At the end a consensus scheme was created, in which a paper was accepted if at least two of the four LLMs agreed on its inclusion and on the following prompt.

You are a professor in computer science conducting a screening for a systematic literature review. Please decide and classify if the following paper belongs to a specific research direction or not. For this, you are provided with the title and the abstract, which should give you sufficient information for an informed and accurate decision. The research direction is the topic of 'Supporting cognitive map acquisition among persons with vision impairments in VR'. Therefore include papers that deal with visually impaired persons, spatial cognition and virtual reality

You MUST discard papers that: focus only on outdoor environments use only sighted participants do not focus on user evaluation do not focus on spatial cognition are purely medicinal are purely technical only focus on navigation aid do not involve virtual reality

You MUST include papers that study virtual reality for visually impaired

With the prompt and consensus scheme, all of the papers were screened using the LLMs. To validate this screening, 40 random papers different from the 20 used for prompt refinement were manually screened. The results from the LLM consensus were compared with the results of the manual screening, which was used as the ground truth. Out of the 40 papers, the LLMs managed to get 9 true positives (agreement on inclusion), 1 false positive (LLMs included an paper that was manually excluded), 28 true negatives (agreement on exclusion) and 0 false negatives (LLMs excluded an paper hat was manually included. Thus the LLM consensus reached precision of 0.9 and recall of 1 on the validation sample. These results suggest that the LLMs make small amount of mistakes and they are of the false positive type, which can be filtered in a later stage of the process.

3.3 Filtering the subpart

The last exclusion of papers was done to filter out papers focusing on recent VR systems which enable acquisition of spatial information for PVI. In this phase papers older than 10 years and those which did not focus on VR (but only on sensory substitution devices) or spatial cognition were excluded. This part was done manually by reviewing titles, abstracts and full texts.

3.4 Included papers

After the exclusion process 21 papers were left, whose full texts were reviewed. The papers are listed in tables 2 and 4.

4 Results and research questions discussion

The contents of the papers were analyzed with the goal of answering the research questions. The findings concerning each one are presented in the following parts.

4.1 RQ1: What techniques are used to create a VR system for PVI?

VR system analysis was divided into several categories in which main approaches and technologies used were identified. The categories found in the SLR are:
Movement - methods of controlling the movement of the users avatar in the virtual environment

- *Stationary* - users stand or sit in place and control the movement of their avatar using an input device
    - *Real turning* - users turn their body in Some systems allowed the user to turn their body to turn the avatar in VR
    - *Fixed* - the user turns their avatar using an input device
- *Real walking* - users control their movement by walking and turning
    - *Free walking* - walking fully free
    - *Treadmill* - walking on a VR treadmill

User input - methods and technologies used to gather user input used for controlling features other than movement (also used for movement control in the cases of *stationary* movement methods).

- *Head tracking* - position tracking of users head, mainly done using head mounted displays and rarely with motion tracking room setups
- *Controller* - controllers capable of tracking their pointing direction
- *Phone* - smartphones capable of tracking their pointing direction
- *Keyboard*
- *Joystick*

Output - modality and type of information given by the system to the user

- *Audio*
  - *Spatial* - simulation of audio feedback from different directions
  - *Physics simulation* - more complex techniques such as simulating audio waves propagation, usually for echo simulation
- *Haptic*
  - *Vibration*
  - *Texture* - tactile texture simulation
  - *Kinesthetic* - kinesthetic feedback such as brakes preventing movement in certain direction

Output trigger - under which circumstances is feedback from the environment given to the user

- *Collision* - upon collision with an object in the virtual environment
  - *Avatar* - collision triggered by the users avatar
  - *Cane* - collision triggered by a virtual white cane
- *Proximity* - based on proximity of an object to the avatar od the user
- *Footsteps* - audio simulation of users footsteps
  - *Loop* - a sound played on repeat
  - *Collision* - footstep sound played on collision, usually using a VR treadmill for detection
- *Ambient* - environmental audio which does not have a goal of streamlining navigation
- *Cues* - audio cues explicitly used for navigation
- *On demand* - feedback generated on demand of the user, mainly using a button or a gesture

Additional features - interaction methods not available in real environments

- *Teleport* - teleportation in the virtual environment
- *Additional info* - additional information about objects such as their name, proximity and size
  - *Sonificaton* - encoding information to different properties of a sound such as pitch, repetitions and volume
  - *TTS* - text to speech

Which systems implemented which features can be seen in table 2. The percentage representation can be found in table 3. The systems reviewed in the SLR were split in the implementation of movement between stationary design and real walking. All the systems used audio for output and two thirds used it in combination with haptic features. The most used interaction method is avatar collision at 47.62% alluding to the use of contact with object for orientation by PVI.

Around a third of the systems used already available VR technology such as head mounted displays with controllers and treadmills modified for PVI, prominent example being Han et al. (2025). A quarter of the implementations aimed for simplicity and affordability using only a smartphone as both an input and output device and for position tracking. Several experiments tried to create their own specialized devices, such as the *Canetroller* by Siu et al. (2020) a white cane connected to a harness simulating both a texture of an object with vibrations and hard contact using brakes preventing movement of the cane. Some systems like *The virtual Cane* in Lahav (2022) try to create a more modified version of reality which incorporate sensory substitution methods to give the user detailed information about an object from a distance, which is normally unavailable to them.

4.2 RQ2: Which features of a VR system improve CM acquisition for PVI?

Numerous findings about the impact of certain features on the experience of users of the VR systems were found in the papers. The mechanisms identified do not necessarily affect the process of CM acquisition directly, but rather the whole experience which facilitates CM acquisition.

4.2.1 Movement

Benefits of free movement were found by Han et al. (2025) who observed better performance in obstacle detection between participants who explored an environment using free walking compared to a group on VR treadmill, which performed better at learning the layout of an environment with mostly perpendicular turns. Kubota et al. (2025) observed that controlling the turning in VR using the real turning of a users body helped users accomplish more complex non-perpendicular rotations easily.

4.2.2 System output and modalities

In terms of output modality Siu et al. (2020) and Zhao et al. (2024) highlight the benefits of using a multimodal feedback in enabling CM acquisition at multiple levels of detail at the same time (such as general layout, and local object details) and increasing CM acquisition efficacy respectively. Kubota et

Tab. 2: Types of VR techniques implemented across the reviewed.

Article	Movement	User input	Output	Output trigger	Additional features
Andrade et al. (2021)	stationary, fixed, controller	head tracking, controller	spatial audio, physics sim., echoes	footsteps loop, on demand	teleport
Cobo et al. (2017)	stationary, real turning	phone	spatial audio, physics sim., echoes	avatar collision, proximity	sonification, TTS, additional info
Guerrón et al. (2020)	stationary, real turning, phone	phone	spatial audio, haptic, vibration	avatar collision, proximity	sonification, TTS, additional info
Han et al. (2025)	real walking, treadmill, free walking	head tracking, controller	spatial audio, haptic, vibration	avatar/cane collision, proximity, cues	—
Júnior et al. (2025)	customizable	head tracking, controller	audio, haptic	avatar collision, proximity	customizable
May et al. (2020)	real walking, free walking	head tracking	spatial audio	cues, proximity	sonification, TTS, additional info
Kreimeier and Götzelmann (2019)	real walking, treadmill	head tracking, controller	haptic, vibration, spatial audio	footsteps collision, avatar collision	—
Kubota et al. (2025)	stationary, real turning	head tracking, controller	spatial audio, haptic, vibration	on demand, cues	—
Kunz et al. (2018)	real walking, free walking	head tracking, controller	spatial audio, haptic, vibration	proximity, cues	sonification, additional info
Lahav et al. (2018)	stationary, fixed, controller	controller	spatial audio	on demand, cues, footsteps loop	TTS, additional info
Lahav (2022)	stationary, fixed, controller, keyboard	controller	spatial audio, haptic, vibration, texture	on demand, cues, footsteps loop	TTS, additional info, teleportation
Merabet and Sánchez (2016)	stationary, fixed, keyboard, joystick	keyboard, joystick	spatial audio, haptic, vibration	ambient, on demand, avatar collision	sonification, additional info
Ochiai et al. (2025)	real walking, treadmill	head tracking, controller	spatial audio	cues	sonification
Cobo et al. (2018)	stationary, real turning, phone	phone	spatial audio, haptic, vibration	avatar collision, proximity	sonification, TTS, additional info
Ricci et al. (2022)	stationary, real turning	head tracking, controller	spatial audio, haptic, vibration	avatar collision	—
Rivière et al. (2019)	stationary, fixed, joystick	joystick	spatial audio, haptic, vibration, texture, kinesthetic	ambient	sonification, TTS, additional info
Seki et al. (2023)	real walking, treadmill	head tracking, controller	spatial audio, haptic, vibration	cane collision, footsteps collision	—
Siu et al. (2020)	real walking, free walking	head tracking, controller	spatial audio, physics sim., haptic, vibration, texture, kinesthetic	cane/avatar collision, cues	—
Tang et al. (2025)	real walking, free walking	head tracking	audio	cues	—
Yeung et al. (2023)	stationary, real turning, phone	phone	haptic, vibration, spatial audio	footsteps loop, cane/avatar collision	—
Zhao et al. (2024)	stationary, real turning, phone	head tracking, phone	haptic, vibration, spatial audio	footsteps loop, cane collision	TTS, additional info

Tab. 3: Percentage of VR techniques in the reviewed papers ($n = 21$).

Feature	%	Feature	%
Movement		*Control*	
stationary	57.14	head tracking	61.90
fixed	23.81	controller	57.14
real turning	33.33	phone	23.81
real walking	38.10	controller	14.29
free walking	23.81	joystick	9.52
treadmill	19.05	keyboard	4.76
keyboard	9.52		
joystick	9.52		
Output modality		*Output trigger*	
audio	100.00	avatar collision	47.62
spatial audio	90.48	cane collision	28.57
physics sim.	14.29	proximity	33.33
haptic	66.67	footsteps loop	23.81
vibration	66.67	footsteps coll.	9.52
texture	14.29	cues	47.62
kinesthetic	9.52	ambient	9.52
multimodal	66.67		
Additional features			
additional info	47.62	vocalization	38.10
sonification	38.10	teleport	9.52

al. (2025) reported that audio feedback is better for general orientation while haptic feedback is better for conveying finer details about the objects. Others like Kunz et al. (2018) and Guerrón et al. (2020) also warn not to overload one modality with too much information as after a certain threshold, the user will stop being able to process all the information and a significant amount of it will be lost.

Andrade et al. (2021) showed that echolocation is an effective way of acquiring spatial information about the layout of an environment for PVI and its addition to VR systems can improve the CM acquisition process. When it comes to audio feedback, ecological validity in terms of realistic sounds mainly in footstep sound and human voice was observed by Andrade et al. (2021) and Ochiai et al. (2025) to be important for the users, as unnatural sounds distracted and frustrated them. May et al. (2020) found that certain landmarks are more important for navigation and should be highlighted using sound cues more saliently than others.

4.2.3 Additional features

Multiple papers found giving users detailed information about distant objects beneficial. Cobo et al. (2018) observed that enabling users to get voice descriptions of objects pointed on lead to users being able to confidently locate objects in an environment. Lahav et al. (2018) and Lahav (2022) used a similar feature for distal exploration which lead to participants having a more allocentric CM model, uncommon between most PVI and remembering more details about the objects in the environment than participants exploring the environment in reality. On the other hand it also severely prolonged the exploration time as the useres needed to get used to this new interaction method. Cobo et al. (2017) used sonification and voice cues to give users information about objects in their line of sight and observed that the enabled distant exploration sped-up and improved the exploration process.

Lastly based on their user research and testing Guerrón et al. (2020) and Lahav et al. (2018) emphasize that intuitive and more simple interfaces are preferred by PVI.

4.3 RQ3: To which extent are cognitive maps acquired in VR usefull in the real environment?

Not many of the reviewed papers did tackle the usefulness of the CM acquired in VR during later use in a real environment. Lahav et al. (2018), Lahav (2022), Guerrón et al. (2020) and Cobo et al. (2017) all asked participants in their evaluations to perform tasks in a real space equivalent of an environment of which the participants acquired a CM beforehand in VR. Lahav (2022) compared participants with a control group which has acquired CM of the environment in a real space and found that exploration of the environment through multisensorial VR systems resulted in spatial ability at a level better or equal to that achieved in real space exploration. Both Guerrón et al. (2020) and Cobo et al. (2017) compared different VR implementations between each other, but no comparison with CM acquired in a real space or task performance without prior exploration of the environment. Cobo et al. (2018) reported that after exploring an environment using their VR system the participants who evaluated the RV applications were able to locate objects and structures within an unknown environment, with confidence and security.

In motivations for their research Han et al. (2025), Júnior et al. (2025), Ricci et al. (2022) and Seki et al. (2023) all emphasize the usefulness of being able to learn about an environment before traversing it using VR as visits without prior knowledge can be dangerous.

4.4 RQ4: What methods are used to evaluate qualities of a CM of PVI?

A broader analysis of evaluation methods used in the papers was done, as most papers evaluated their VR systems based on the quality of the CM acquired using it. The result of the analysis is the table 4 describing the evaluation type, metrics, methods and participant sample and table 5 presenting the percentages of each in the population of the reviewed papers. The papers used mostly mixed evaluation with a third of them using just quantitative methods. Qualitative methods were used exclusively for evaluating the VR systems and included post-task interviews, questionnaires and surveys.

All the studies presented the participants with a task which required using a CM acquired in VR. The tasks were too varied to categorize them, but the most common ones were walking from point A to point B in the environment and listing all the objects and their positions in the environment. The task performance was evaluated using different metric, the most common being success rate among the participants, completion time of the task and number of collisions with the environment during the task. 8 papers also employed CM externalization methods in which they instructed the participants to recreate the environment, most commonly using verbal reconstruction and assembling a model from prebuilt parts.

5 Limitations

The findings of the papers reviewed in this SLR are subject to two main limitations. The first one is mentioned in most of the papers themselves and it concerns the small sizes of participant groups used for evaluation with the mean being 12.43. Several studies also did not disclose the severity of the visual impairment of their participants and some used blindfolded sighted participants limiting the ecological validity. Secondly the studies used different methodologies for evaluating the acquired spatial knowledge and the implemented VR systems.

The SLR itself has limitations in its smaller sample of 21 reviewed papers, which were sourced from only two digital libraries. Validity of the screening process could also be questioned as it was partially automated using LLMs. In an attempt to address this limitation, the evaluation of the screening results was done as described in part 3.2

6 Discussion

This review presents several suggestions for creating a VR system suited the most for CM acquisition combining the findings from answers to the research questions.

Based on the benefits discussed in section 4.2.1 a movement method using free walking and real turning seems best suited for acquisition of more spatial knowledge of more complex environments. Input devices which are capable of tracking position and pointing direction are preferable as they can be used to implement additional features using the direction the user is pointing to such as presenting information about distant objects or being a point of origin of a virtual cane. The interface of using the system should be simple to be more usable by the target user base.

Based on the findings in section 4.2.2 the system should provide the used with multimodal feedback, where each modality gives information about the environment at a different level of detail, with audio being used for more general information and haptic feedback for details about individual objects. Echo simulation should be implemented to enable orientation by echolocation. The system must be tested to ensure that the users are not overloaded with information from a single modality.

Enabling the user to gain detailed information about distant objects upon request would support acquisition of allocentric spatial knowledge as described in section 4.2.3.

To be equipped for evaluating the CM acquired using it as in ways presented in section 4.4, the VR system should feature methods to create and complete tasks in the environment and subsequently measure if the task was successful and how long it took. Additionally a system measuring if the user is pointing to specific object for object localization tasks could also be beneficial.

Papers such as Cobo et al. (2018) and Lahav et al. (2018) also highlighted the importance of participatory design and creating system requirements based on user studies, as this process can eliminate usability issues and identify effective interaction methods early in the development.

7 Conclusion and future work

This paper presented a SLR of recent papers concerning VR systems which enable acquisition of spatial information for PVI. From initial 574 papers found across two digital libraries 21 were included and their full texts reviewed. The review served to answer four research question which would help to create a source of information from which requirements of a VR system for CM acquisition for PVI could be created. In the discussion section suggestions for the requirements of the potential system were presented.

While the field of VR systems facilitating CM acquisition for PVI is populated with various promising approaches certain research gaps were identified in the SLR. This mainly concerns the evaluation of the CM acquisition, such as examining the usefulness of the acquired CM in a real environment, comparing

Tab. 4: Evaluation methods and participant samples across reviewed papers.

Article	Evaluation type	Quantitative metrics	Qualitative methods	CM extern.	Participant total	Participant breakdown
Andrade et al. (2021)	mixed	success rate, completion time, feature usage	interview	clay	12	9 totally blind, 12 with visual impairment
Cobo et al. (2017)	quantit.	success rate, exploration time	—	model	19	19 with visual impairment
Guerrón et al. (2020))	mixed	success rate, exploration time	—	model	20	20 with visual impairment
Han et al. (2025)	mixed	success rate, completion time, collision count	interview, quest.	—	16	3 totally blind, 16 with visual impairment
Júnior et al. (2025)	*without evaluation*					
May et al. (2020)	mixed	success rate	interview, quest.	model, verbal	8	8 with visual impairment
Kreimeier and Götzelmann (2019)	mixed	success rate	questionnaire	—	6	3 totally blind, 3 sighted
Kubota et al. (2025)	mixed	success rate	interview	rewalk	6	6 with visual impairment
Kunz et al. (2018)	quantit.	collision count	—	—	13	13 with visual impairment
Lahav et al. (2018)	mixed	complex task evaluation	—	—	10	5 totally blind, 5 sighted
Lahav (2022)	mixed	success rate	quest., observation	verbal	15	15 with visual impairment
Merabet and Sánchez (2016)	quantit.	success rate, completion time, path	—	—	0	—
Ochiai et al. (2025)	quantit.	task accuracy	—	—	18	—
Cobo et al. (2018)	mixed	success rate	questionnaire	—	15	15 with visual impairment
Ricci et al. (2022)	mixed	success rate, completion time, collision count	questionnaire	—	50	50 with visual impairment
Rivière et al. (2019)	quantit.	success rate	—	—	14	7 totally blind, 3 sighted, 4 with visual impairment
Seki et al. (2023)	quantit.	success rate, completion time	—	—	3	3 with visual impairment
Siu et al. (2020)	mixed	success rate, completion time, collision count	interview	—	8	5 totally blind, 3 sighted
Tang et al. (2025)	quantit.	completion time, collision count	—	—	7	3 totally blind, 7 with visual impairment
Yeung et al. (2023)	mixed	task accuracy	survey	verbal	6	6 with visual impairment
Zhao et al. (2024)	mixed	task accuracy	survey	verbal	15	12 with visual impairment

Tab. 5: Frequency of evaluation characteristics across reviewed studies ($n = 21$).

Feature	%	Feature	%
Evaluation type		*Quantitative metrics*	
mixed	61.90	success rate	47.62
quantitative	33.33	completion time	33.33
without evaluation	4.76	collision count	23.81
qualitative	0.00	task accuracy	14.29
		exploration time	9.52
		complex task eval.	4.76
		feature usage	4.76
Qualitative methods		*CM externalization*	
questionnaire	23.81	without	61.90
interview	23.81	verbal	19.05
survey	9.52	model	14.29
observation	4.76	rewalk	4.76
		clay	4.76

the acquisition process with other non-VR methods and comparing the CM acquired with a virtual white cane and without it.

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References

Andrade, R., Waycott, J., Baker, S. and Vetere, F. (2021). Echolocation as a means for people with visual impairment (pvi) to acquire spatial knowledge of virtual space. *ACM Trans. Access. Comput.*, 14(1).

Chebat, D.-R., Schneider, F. C. and Ptito, M. (2020). Spatial competence and brain plasticity in congenital blindness via sensory substitution devices. *Frontiers in Neuroscience*, 14:815.

Cobo, A., Guerrón, N. E., Martín, C., del Pozo, F. and Serrano, J. J. (2017). Differences between blind people's cognitive maps after proximity and distant exploration of virtual environments. *Computers in Human Behavior*, 77:294–308.

Cobo, A., Serrano Olmedo, J. and Guerron, N. (2018). Methodology for building virtual reality mobile applications for blind people on advanced visits to unknown interior spaces.

Façanha, A. R., Darin, T., Viana, W. and Sánchez, J. (2020). Om indoor virtual environments for people who are blind: A systematic literature review. *ACM Trans. Access. Comput.*, 13(2).

Guerrón, N. E., Cobo, A., Serrano Olmedo, J. J. and Martín, C. (2020). Sensitive interfaces for blind people in virtual visits inside unknown spaces. *International Journal of Human-Computer Studies*, 133:13–25.

Han, S., Yoon, P., Ren, X. and Kim, K. (2025). The effects of walk-in-place and overground walking on the acquisition of spatial information by people with visual impairment in virtual reality wayfinding. *International Journal of Human–Computer Interaction*, 41(4):2541–2559.

Joos, L., Keim, D. A. and Fischer, M. T. (2026). Leveraging llms for semi-automatic corpus filtration in systematic literature reviews. *Computers Graphics*, 135:104537.

Júnior, J. M. L. d. M., Façanha, A. R., Silva, B. C. d., Viana, W. and Santos, J. d. (2025). Enhancing orientation and mobility skills for persons with visual impairments through vr games: Introducing the edkit unity package. Figueroa, P., Di Iorio, A., Guzman del Rio, D., Gonzalez Clua, E. W. and Cuevas Rodriguez, L. (ed.), In *Entertainment Computing – ICEC 2024*, pp. 232–241, Cham. Springer Nature Switzerland.

Kreimeier, J. and Götzelmann, T. (2019). First steps towards walk-in-place locomotion and haptic feedback in virtual reality for visually impaired. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI EA '19, pp. 1–6, New York, NY, USA. Association for Computing Machinery.

Kubota, M., Kuribayashi, M., Ribeiro, R. A. and Morishima, S. (2025). Investigating blind people's route perception of complex pre-mapped routes in virtual reality. In *Adjunct Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology*, UIST Adjunct '25, New York, NY, USA. Association for Computing Machinery.

Kunz, A., Miesenberger, K., Zeng, L. and Weber, G. (2018). Virtual navigation environment for blind and low vision people. Miesenberger, K. and Kouroupetroglou, G. (ed.), In *Computers Helping People with Special Needs*, pp. 114–122, Cham. Springer International Publishing.

Lahav, O. (2022). Virtual reality systems as an orientation aid for people who are blind to acquire new spatial information. *Sensors*, 22(4).

Lahav, O., Gedalevitz, H., Battersby, S., Brown, D., Evett, L. and Merritt, P. (2018). Virtual environment navigation with look-around mode to explore new real spaces by people who are blind. *Disability and Rehabilitation*, 40(9):1072–1084.

May, K. R., Tomlinson, B. J., Ma, X., Roberts, P. and Walker, B. N. (2020). Spotlights and soundscapes: On the design of mixed reality auditory environments for persons with visual impairment. *ACM Trans. Access. Comput.*, 13(2).

Merabet, L. and Sánchez, J. (2016). Development of an audio-haptic virtual interface for navigation of large-scale environments for people who are blind. vol. 9739, pp. 595–606.

Ochiai, Y., Tsuji, A., Aihara, S. and Iwata, H. (2025). Virtual reality assessment of auditory spatial perception and navigation in blind football players. In *2025 IEEE International Workshop on Sport, Technology and Research (STAR)*, pp. 215–220.

Ottink, L., Buimer, H., van Raalte, B., Doeller, C. F., van der Geest, T. M. and van Wezel, R. J. (2022). Cognitive map formation supported by auditory, haptic, and multimodal information in persons with blindness. *Neuroscience & Biobehavioral Reviews*, pp. 104797.

Ricci, F., Boldini, A., Beheshti, M., Rizzo, J.-R. and Porfiri, M. (2022). A virtual reality platform to simulate orientation and mobility training for the visually impaired. *Virtual Reality*, 27.

Rivière, M.-A., Gay, S., Romeo, K., Pissaloux, E., Bujacz, M., Skulimowski, P. and Strumillo, P. (2019). Nav-vir: an audio-tactile virtual environment to assist visually impaired people*. pp. 1038–1041.

Seki, R., Shimomura, Y., Asakawa, N. and Wada, H. (2023). Development of orientation and mobility training system for visually impaired children using vr. *Studies in health technology and informatics*, 306:527–534.

Siu, A. F., Sinclair, M., Kovacs, R., Ofek, E., Holz, C. and Cutrell, E. (2020). Virtual reality without vision: A haptic and auditory white cane to navigate complex virtual worlds. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, pp. 1–13, New York, NY, USA. Association for Computing Machinery.

Tang, J., Shi, R. and Gu, L. (2025). *An Immersive Virtual Reality Training System for Enhancing Orientation and Mobility in Individuals with Visual Impairments*, pp. 381–393.

Yeung, R., Oyekoya, O. and Tang, H. (2023). In-place virtual exploration using a virtual cane: An initial study. In *Companion Proceedings of the 2023 Conference on Interactive Surfaces and Spaces*, ISS Companion '23, pp. 45–49, New York, NY, USA. Association for Computing Machinery.

Zhao, H., Oyekoya, O. and Tang, H. (2024). Enhancing virtual mobility for individuals who are blind or have low vision: A stationary exploration method. In *Companion Proceedings of the 2024 Conference on Interactive Surfaces and Spaces*, ISS Companion '24, pp. 83–87, New York, NY, USA. Association for Computing Machinery.