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ORIGINAL ARTICLE

Use of augmented reality in human wayfinding: a systematic review

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Abstract
Augmented reality(AR) technology has emerged as a promising solution to assist with wayfinding difficulties,bridging the gap between obtaining navigational assistance and maintaining an awareness ofone's real-world surroundings. In this article, we present a systematic review of researchliterature related to AR navigation technologies. An in-depth analysis of 88 salient studies wasconducted to address four main research topics: (1) the current state-of-the-art of ARnavigational assistance technologies, (2) user experiences of interacting with these technologies, (3) the effect of AR on human wayfinding performance, and (4) the impacts of AR for humannavigational cognition. We noted a recent rise in unified solutions for AR navigational assistance,with advancements in mobile devices, head-mounted displays, and versatile third-partyplatforms. A robust body of literature has demonstrated reductions in cognitive load andimproved cognitive map development when using these AR technologies, in comparison totraditional guidance modalities such as paper maps. However, findings about wayfindingperformance and user experience were mixed. For example, performance improvementsassociated with AR have been consistently demonstrated in indoor environments, butresearchers have not found similar advantages in outdoor environments. The research indicatesthat within AR visual guidance tends to be more effective than auditory cues, and that theincorporation of overview maps greatly improves the performance benefits of AR. While usersgenerally described AR navigational assistance in positive terms, they also reported specificchallenges related to hardware, localization techniques, and frustrating interfaces. The articlediscusses these nuances in detail while overall lending support to the conclusion that AR has agreat potential to enhance wayfinding by providing enriched navigational cues, interactiveexperiences, and improved situational awareness.

Keywords Augmented Reality; User Experience; Spatial Cognition; Wayfinding Performance; Systematic Review

1 Introduction

Wayfinding is a complex cognitive process that requires assimilating spatial information from the environment, applying problem-solving skills, and making and executing decisions to reach a destination (Passini 1996). This can be challenging for many people, especially in complex modern environments such as hospitals, airports, and large office buildings, which have been associated with wayfinding struggles that may potentially lead to negative practical and psychological outcomes (Arthur and Passini 1992; Carpman and Grant 2002). For example, wayfinding problems in healthcare settings can lead to confusion, anxiety, frustration, stress, elevated blood pressure, and fatigue, as well as to missed appointments (Schmitz 1997; Shumaker and Reizenstein 1982). To address these problems, technologies such as Augmented Reality (AR) have been introduced to aid wayfinding behaviors and assist in developing internal cognitive maps (Zhang et al. 2021). In contrast to Virtual Reality (VR), which immerses the user in a completely artificial virtual environment, AR overlays computer-generated navigation instructions onto the real environment using mobile real-time camera screens or head-mounted displays (HMDs), allowing users to remain engaged with their surroundings by not having to split their attention away to a separate device for navigational guidance (Azuma 1997; Barra et al. 2024; Rusch et al. 2013).

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The rapid development of this technology has been associated with an explosion of AR wayfinding research, with a substantial increase in the annual number of publications over the past decade. A great deal of this research has been focused on technical challenges, such as the need for reliable localization and tracking methods to synchronize the AR displays with the user's real-world viewpoint. Such methods may involve Simultaneous Localization and Mapping (SLAM), the use of automated registration data to create large-scale 3D model of the surrounding environment (Radanovic et al. 2023), or hybrid tracking that integrates multiple data sources such as Global Positioning System (GPS) and Inertia Measurement Units (IMUs) consisting of accelerometers, gyroscopes, and magnetometers (Delgado et al. 2020). Equally important is the development of robust pathfinding algorithms capable of devising optimal routes for users based on their current locations and the environmental conditions. AR interaction modalities have also diversified significantly, incorporating gesture recognition, touch interaction, and voice commands, among others.

In addition to these technical challenges of AR, there are several research gaps in understanding how users interact with AR-assisted wayfinding systems on a cognitive and experiential level. Understanding experiential quality is essential, as factors such as usability, acceptance, and immersion play a crucial role in the adoption and effectiveness of navigational aids (Arifin et al. 2018; Slater and Wilbur 1997). While AR has generally been shown to improve measures of wayfinding performance, such as task completion time and distance traveled (Zhang et al. 2021), comparative studies that systematically assess its effectiveness against traditional navigational support, such as digital and paper maps, are limited. Often the performance measures, experimental conditions, and types of technologies used in various studies are incommensurate with each other, making it difficult to conduct direct comparisons of the research outcomes. Moreover, the cognitive implications of interacting with AR systems, such as their impact on cognitive load and the development of cognitive maps, remain insufficiently explored (Kalyuga 2011; Tolman 1948). Usability challenges, such as discomfort over long-term use, tracking and lagging issues, and misalignment of virtual content with real environments, have all been reported to potentially contribute to negative effects on cognitive load and task performance (Montuwy et al. 2019; Rehman and Cao 2017; Zhao et al. 2020).

This highlights the necessity for a comprehensive review of research on AR navigation systems, particularly on studies related to user experience (UX). At the current time there is a great deal of emerging research literature in this area, but a lack of summary overviews that compare and synthesize the overall state of the field. The primary objective of the current literature review was therefore to evaluate and summarize recent research on AR-assisted wayfinding as related to UX, wayfinding performance, and cognitive impacts. To maintain a precise scope and avoid potential issues of ecological validity, we included only studies of real-world navigation using AR technologies. Studies of navigation (augmented or not) in fully virtual environments were excluded. To guide the review, we formulated the following four research questions:

RQ1. What is the current state-of-the-art of AR navigational assistance technologies?

RQ2. What consensus knowledge has emerged about factors related to the user experience and acceptance of these technologies?

RQ3. Does the research literature consistently show an effect of AR navigational assistance on human wayfinding performance?

RQ4. What are the impacts of AR navigational assistance on human perception, decision-making, behavior, and cognition?

The next section of the paper provides a background overview of AR and its applications in the context of human wayfinding. We then present the methods for the current literature review, followed by a comprehensive summary of our findings. The discussion section analyzes and interprets these results in light of the four research questions outlined above. Finally, we conclude by identifying challenges, trends, and recommendations for future directions in research and practice.

2 Background

There are three foundational topics undergirding our approach in this review, which will be explained in the following sub-sections. These include the technological state-of-the-art in current AR devices, concepts related to AR user experience, and concepts related to guided wayfinding.

2.1 AR navigation systems

Augmented Reality is a technology that overlays computer-generated virtual content onto the real world, so that the virtual information is aligned with real-world objects and can be viewed in real time (Azuma 1997). The two main approaches to AR include the use of a screen with a real-time video feed, or the use of transparent head-mounted displays ("smart glasses") to present information. For many years, such AR technologies were confined to research laboratories and military training applications. The advent of tracking systems for mobile phones in the early 2000s marked a pivotal point in the evolution of AR systems, eventually leading to the maturation of the technologies and their assimilation into everyday devices (Chatzopoulos et al. 2017). Wayfinding assistance was one of the first and most central uses of AR technologies, with early adopters relying on smartphones and designated visual markers to enhance indoor navigation. For example, Möller et al. (2014) demonstrated a localization technique using image recognition, in which camera-captured images that matched those in an image library would trigger navigational instructions such as arrows and distance-to-destination superimposed onto the phone's screen. These approaches ultimately evolved into complex AR head-mounted displays that show path visualizations, anchored signs, and layout maps while allowing users to interact with virtual objects via hand-gestures (Oh et al. 2017; San Martin and Kildal 2021).

In general, AR navigation systems are grounded in three core components. First, localization techniques are used to determine the user's current location and often their specific field of view to align virtual information with the real environment. GPS is primarily used for localization in outdoor scenarios, while indoor navigation employs diverse localization methods, including SLAM, QR code-based markers, and some combinations of IMUs, Bluetooth beacons, or image-recognition technologies (Delgado et al. 2020). Some AR applications have used spatial mapping, often through cameras or laser scanners, to allow more robust tracking of user positions by producing a detailed 3D representation of the environment within the technological system (Weinmann et al. 2021; Radanovic et al. 2023). Second, algorithmic path-generation is used to determine an optimal route from the user's current location to their intended destination by applying pathing algorithms such as Dijkstra (Fan and Shi, 2010) or A* (Duchoň et al. 2014). Finally, the AR system presents visual or auditory instructions overlaid onto the real environment through handheld devices or HMDs, which may include a combination of 2D overview maps, action-signs, turn-by-turn directions, and/or supplementary points-of-interest information (Lu et al. 2021; Oliveira de Araujo et al. 2019; Zhang et al. 2021; Zhao et al. 2020).

2.2 Defining and measuring user experiences of AR

Our definition of the overall user experience (UX) within the context of AR includes the elements of emotional responses, interface preferences, physical interactions, and psychological reactions (Arifin et al. 2018; Dirin and Laine 2018). This experience is an evolving process, unfolding in accordance with the technology's features as the user interacts with the AR device throughout the navigation process. In general, the broad construct of usability refers to the extent to which a technology is perceived as helpful for achieving one's goals effectively, efficiently, and enjoyably (Brooke 1996; Davis 1989; International Organization for Standardization 1998). Aspects of user experience that have been described as particularly salient for AR technologies include: (a) the ability to quickly and easily familiarize oneself with the technology during first contact, (b) the ability to use the technology while moving through a real-world environment without excessive distraction, and (c) the ability to remember the system's functions across multiple sessions (Punchoojit and Hongwarittorrn 2017). AR systems feature a range of devices and technologies, each of which may have different user experiences. Handheld devices for AR require continuous holding and may provide greater interference with environmental immersion, while HMDs can be more conspicuous but provide a convenient hands-free experience. These devices are sometimes supplemented with additional sensory equipment, such as wearable haptics for tactile feedback and biometric sensors that monitor physiological responses (e.g., heart rate). UX quality can be enhanced by accommodating diverse preferences in regard to AR interaction modalities or interfaces. This includes a wide range of interactions, from tap, drag, and pinch gestures to voice commands, along with diverse localization techniques such as visual markers or image recognition. User preferences also vary, with some people favoring visual guidance vs. auditory cues, and with different preferences for turn-by-turn instructions or overview maps (Zhao et al. 2020; Zhang et al. 2021). The extent to which people accept and embrace novel technologies is closely tied to such usability factors and can be empirically measured via scales such as the Technology Acceptance Model (TAM) (Tom Dieck and Jung 2018).

We also address in this paper a related construct of "attitude" or disposition toward AR technology, which focuses on responses such as trust, confidence, and satisfaction (Hassenzahl 2018). Trust may be affected by the predictability of the system's behavior, prior experiences indicating that the system is dependable in achieving the user's goal, and general perceptions of related technologies (Muir 1994). In addition to designing a well-performing system, trust can be improved through clear instructional materials and by emphasizing robust security measures to protect user data. This is highly important since a lack of trust can have a significant impact on users' acceptance of AR systems (Corritore et al. 2003). Attitudes toward AR technologies can also be improved by designs that incite positive emotions (pleasantness, excitement) and that minimize negative emotions (frustration, confusion) (Norman 2004).

In AR navigational assistance systems, users' perception of the informational and physical environment is crucial. We define visual perception in AR as the identification and interpretation of sensory information, such as depth of field, when it comes to the overlayed positioning of virtual objects in the physical world (Schacter et al. 2011; Kim et al. 2018). Achieving fluid visual perception in AR requires very precise localization algorithms as well as an effective design of the virtual elements. Misalignment between virtual information and the real world can lead users to overly focus on their devices, resulting in increased disorientation, uncertainty, and reduced awareness of their surroundings, potentially leading to navigational errors and severely eroding the UX aspects of the technology (Montuwy et al. 2019). In contrast, well-aligned perceptual elements can enhance users' situational awareness, promoting a comfortable understanding of where one is, where one is going, and what is happening in the surroundings (Endsley 1995).

The concepts of immersion and presence are also useful for analyzing users' interactions with AR technologies. We define immersion in AR as the extent to which a user feels fully engaged or absorbed in the virtual content, perceiving it as a fluid extension of their overall subjective experience of the environment (Slater and Wilbur 1997). Fidelity, spatial stability, interactivity, and coherence with the real-world context are all important for achieving AR immersion (Bowman and McMahan 2007; Slater 1999). Presence is a related construct that describes the subjective sensation of "being" within the augmented environment rather than just engaging with a technological overlay. This experience, in which the distinction between the physical world and the virtual AR components fades from users' awareness, is affected by the fidelity of the technological components but is also profoundly shaped by the realism and emotional engagement of the virtual content (Slater and Steed 2000). Presence has been consistently correlated with higher satisfaction levels in multiple types of virtual and augmented environments (Slater and Wilbur 1997; Bulu 2012), as well as with better task performance and learning in these environments (Cen et al. 2019; Loup-Escande et al. 2017). Therefore, studying UX components in AR navigation systems is a vital aspect of improving their effectiveness.

2.3 Foundational concepts in wayfinding cognition

Wayfinding cognition refers to the complex mental processes involved in human navigation through physical spaces, including understanding, planning, and executing a route from one location to another (Montello 2005). It involves both conscious and unconscious thought, memory, perception, and spatial problem-solving, and encompasses various forms of spatial memory. Spatial memories themselves can be categorized into three types: landmark knowledge (concerning specific, easily recognizable points in the environment); route knowledge (sequences connecting objects or places); and survey knowledge (an understanding of distances and spatial relationships throughout the environment) (McNamara 2013; O'Keefe and Nadel 1979; Siegel and White 1975). All three types of spatial memory are relevant for the dynamic, ongoing formation of cognitive maps, the mental representations that allow individuals to visualize and reason about spatial relations (Tolman 1948). Recent studies of navigation have added the concept of "cognitive graphs," which focus on idiothetic information such as path lengths and junction angles as a way of remembering routes (Warren et al. 2017). Current research seems to indicate that human wayfinders rely on both cognitive maps and cognitive graphs, in varying and individualistic combinations, when completing wayfinding activities (Peer et al. 2021). In theory, the transparent overlay of information onto the real-world environment could encourage more active cognitive engagement. However, research conducted in this area is limited, and prior studies examining AR navigational aids and cognitive map development have produced mixed results. Some studies have suggested a positive correlation between AR navigational beacons and virtual landmarks and spatial knowledge acquisition (Liu et al. 2021; Stefanucci et al. 2022). Conversely, other studies have indicated that AR users may pay less attention to their environment compared to traditional aids, potentially hindering the formation of cognitive maps (Rehman and Cao 2017). Comprehensively understanding the role of AR-assisted tools in cognitive map formation, especially in comparison to traditional navigational aids, is crucial, as it directly impacts navigational efficiency in various settings.

Cognitive Load Theory posits that human working memory, essential for learning and problem-solving, is limited in capacity and requires significant energy to maintain (Buchner et al. 2021). This concept has emerged as a central topic in AR navigation research, under the assumption that AR navigational tools can help to reduce cognitive load, especially when compared against other kinds of navigational devices. The theory stipulates that cognitive load has an intrinsic component, related to task complexity; an extraneous component, tied to the features and design of the environment; and a germane component, concerned with the construction of mental schemas (Kalyuga 2011; Sweller et al. 1998). The often-stated goal of AR navigational technologies is to reduce the extraneous load and thus, indirectly, the germane load (Paas and van Merriënboer 2020). Some prior studies have shown that wearable AR displays can in fact reduce cognitive load during wayfinding and spatial assembly tasks (Deshpande and Kim 2018; McKendrick et al. 2016). However, the specific design of the AR system is likely relevant in this context, as an excess of information or a poorly designed interface could potentially add to, rather than reduce, the user's cognitive load. The mental effort involved in initial familiarization with the technology is relevant as well, and this may be an important consideration in studies that recruit participants who have no prior experience with AR and then end the research after only a few minutes of exposure. The topic of mental effort is a significant consideration in this research area because the goal of navigational AR is to enhance the wayfinding experience, and high cognitive loads may result in poor usability, a lack of acceptance, and reduced effectiveness.

3 Methods

We conducted a systematic literature review to identify, evaluate, and synthesize the existing body of relevant scholarship (Fink 2019; Xiao and Watson 2019). The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) method was used to guide the screening and analysis (Liberati et al. 2009).

3.1 Search strategy

We conducted a search of published academic studies in February of 2023, followed by an additional catch-up review in December of 2024. The reviews' protocol was registered with the Open Science Framework (OSF). To help ensure that we evaluated a wide-ranging and varied array of published articles, four databases were chosen, including Scopus, Web of Science, IEEE Xplore, and the ACM Digital Library. All of these databases cover a broad range of scientific publications, rendering them highly suitable for our project's goals.

The following terms were used to search article titles, abstracts, keywords, and subject headings: *("Augment* Reality" OR "Mixed Reality" OR "HoloLens") AND ("Pedestrian Navigat*" OR "Indoor Navigat*" OR "Outdoor Navigat*" OR "Wayfinding" OR "Way-Finding" OR "Pathfinding" OR "Path-Finding" OR "Spatial Cognition").* This string was intended to cover variations of the relevant words (e.g., navigation vs. navigating) and closely related concepts that are often used interchangeably (e.g., augmented reality vs. mixed reality), while still keeping the search narrow enough to exclude the much broader literature on virtual reality. The term HoloLens (Microsoft Corporation HoloLens 2025) was included since it is the most commonly used brand of AR headset. We consulted with an evidence synthesis librarian at our university to carefully formulate and apply this search string so that the review would achieve an effective scope. The results as of December 2024 included 1,036 items from Scopus, 713 from Web of Science, 496 from IEEE Xplore, and 283 from the ACM Digital Library.

3.2 Eligibility criteria and screening of studies

To ensure relevance, rigor, and coherence in the compilation of data, we established clear inclusion and exclusion criteria. To be *included* in the review, an item was required to satisfy all of the following conditions:

(i1) Published in peer-reviewed journals or peer-reviewed conference proceedings. This criterion helps to ensure the quality and credibility of the research.
(i2) Based on empirical study. We only considered articles that incorporated observations and measurements of empirical phenomena. Opinion articles and those based purely on theory were not included.
(i3) Addressed the use of AR technologies with mobile devices and HMDs for pedestrian navigation (either indoor or outdoor).

Items were *excluded* if they fell into one or more of the following categories:

(x1) Dissertations, books, book chapters, overview articles, editorials, conference posters, workshops, and literature reviews (scoping, systematic, meta-analysis, integrative reviews) were excluded from the study. These types of publications were excluded because they generally present overviews or summaries of research fields, rather than providing new empirical data.
(x2) Items not written in English were excluded due to the potential for language barriers to negatively affect the accurate interpretation and analysis of the research.
(x3) Papers that focused primarily on virtual reality, rather than AR or mixed reality, were excluded. Our review covered the use of AR to support real-world wayfinding and did not address the issue of navigating in purely virtual environments.
(x4) Papers that focused primarily on non-pedestrian navigation, for example navigation while driving an automobile, were excluded. Our review only covered the use of AR in pedestrian wayfinding.

Figure 1 presents a PRISMA flowchart for our article selection process, which was the same for the 2023 and 2024 reviews (the indicated article totals are for December 2024). We first used the Covidence software platform (Veritas Health Innovation 2025) to automatically remove duplicate studies. The remaining 1,138 articles were screened by abstract in accordance with our inclusion criteria. During this abstract screening phase, most of the studies that were removed did not address pedestrian navigation and were thus beyond the scope of our review. We found that a large number of papers on self-driving automobiles had slipped

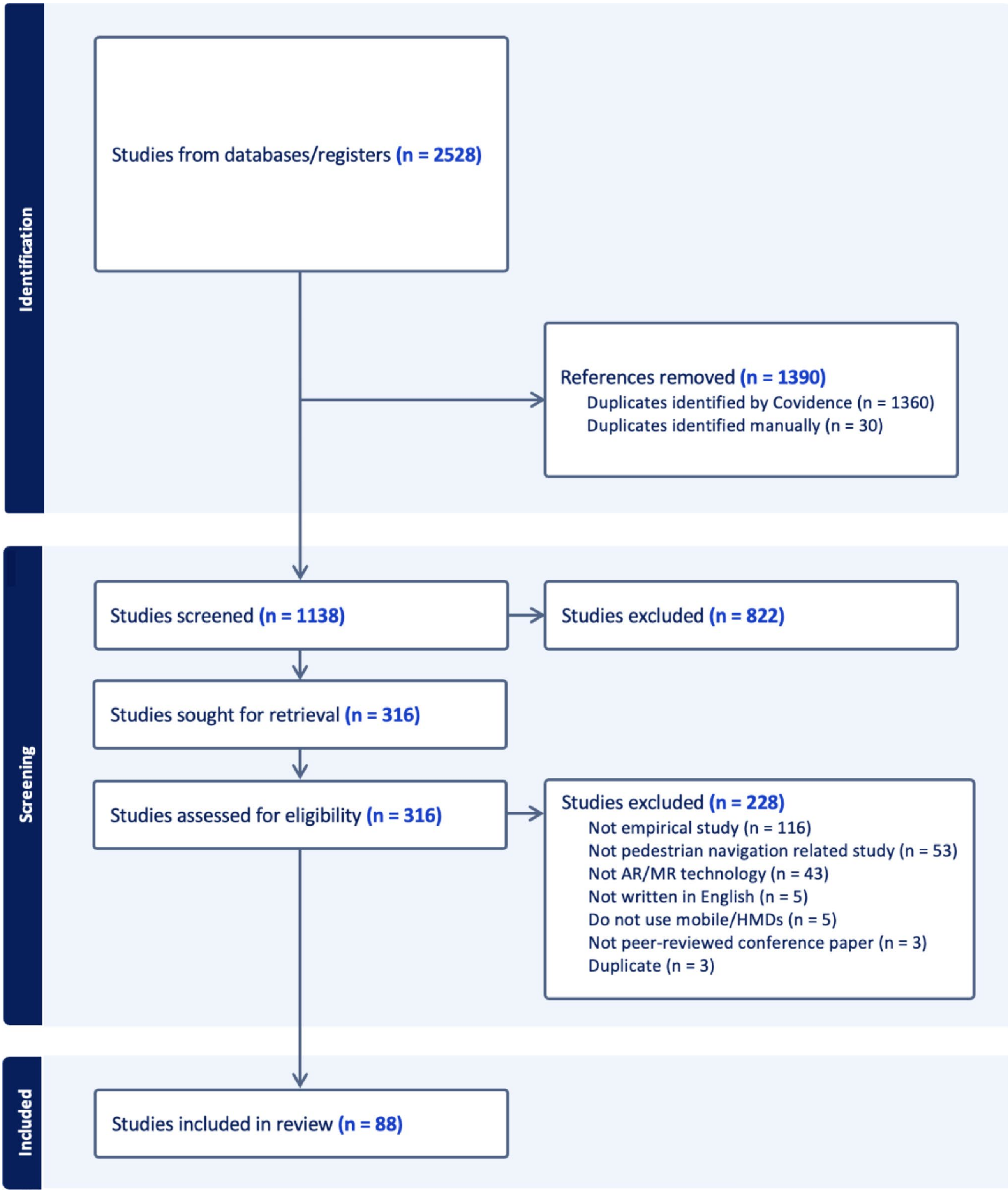

Fig. 1 PRISMA flowchart showing the selection of studies

through our search criteria, as well as a large number of papers on AR development that did not focus on any type of navigational application. After the abstract screening, 316 items were retrieved for full-text eligibility evaluation. In this phase, the majority of the removed studies did not use empirical research methods, which lacked user involvement in experiments related to user experience, wayfinding performance or cognitive aspects. Additional exclusions were made for studies not focusing on pedestrian navigation, such as those concerning car or robot navigation. Others were excluded for utilizing screen-based navigation technologies or custom-designed augmentations that did not pertain to mobile or HMD-related AR/MR, among various other breaches of the inclusion/exclusion criteria. At the end of the multi-stage screening process, 88 studies remained. A short description of each included study is given in Table 1.

3.3 Quality assessment

To evaluate the quality of the included articles, we used the Mixed Methods Appraisal Tool (MMAT) within the Covidence platform (Hong et al. 2018). This tool provides a detailed checklist to assess articles used in systematic reviews, taking into account the type of research conducted in each article. Based on our evaluation, 9 of the articles were found to be qualitative research, 23 were found to be quantitative research, and 56 were mixed methods studies. To ensure consistency, two researchers each reviewed all articles separately and then discussed the interpretation and finalized quality score for each study as a group. The quality score calculations were conducted for these categories according to the MMAT and as discussed by Evangelio et al. (2022). Each item was scored as Yes (1), Cannot tell (0.5), and No (0). Each article in qualitative and quantitative categories had a total score of 7 (2 screening questions and 1 section), while the mixed methods one had 17 (2 screening questions and 3 sections), hence scores of studies in the former categories were scaled up to 17. The results showed that 31 studies were scored below 7 while the rest were well above 10. Although the overall quality of the included studies was sound, several methodological issues were common across studies with lower quality. Many studies failed to consider potential demographic differences in design or analysis (n = 30). Other methodological issues included: failing to provide clear research questions and/or did not address research questions with collected data (n = 23), using unsuitable custom designed measures and/or failing to provide reliability data of these measures for experiment outcomes (n = 23), failing to interpret findings adequately from experimental data (n = 19), and failing to integrate results from qualitative and quantitative components (n = 14). "Appendix" shows a summary of this assessment.

3.4 Data extraction and analysis

We created a standardized form for summarizing the articles' contents, and then divided the 65 articles among the two researchers for review. In addition to recording the year of publication, authors' names, type of publication, and the name of the publication outlet, we summarized each study's content in the following categories: (a) research questions and hypotheses; (b) environmental settings or context; (c) country in which the study took place; (d) specific AR technology used; (e) experiment design; (f) independent, dependent, and mediating variables; (g) number of participants and demographic breakdowns (including age and any medical conditions studied); (h) summary of results; (i) limitations and recommendations; and (j) other pertinent information. For most of these categories, we established predefined codes that could be readily applied, while remaining open to studies that might not fit within our a-priori schema. For example, under the category of experiment design we included codes such as between-subjects, within-subjects, or factorial design. Similarly, to understand the studies' results, we identified whether the studies were oriented towards technological advancements, user experience, wayfinding performance, or spatial cognition. In addition to applying these codes we noted the particulars of the results and any notable findings. Finally, we also recorded the number of citations for each article according to Google Scholar as of June 15, 2023. After summarizing all of the studies in this fashion, we carefully reviewed and discussed the collected literature to identify emerging areas of consensus and contradiction.

4 Results

The literature review provided robust answers to our four research questions, as presented in the following sections.

4.1 The current state-of-the-art of AR navigational assistance technologies (RQ1)

AR navigation system has applied a variety of technologies to superimpose real-time, context-aware information onto the user's field of view. Key components of the system that were frequently addressed in the reviewed literature include the display device, localization methods for precise user positioning, and the interface design.

4.1.1 Display devices

Smartphones and tablets have become prominent platforms for AR displays due to their ubiquity and inherent technological capabilities. Among the papers we reviewed, 53 used smartphones, 2 used tablets, 2 used both smartphones and tablets, and 1 used both smartphones and HMDs (Table 1). Since today's smartphones are almost universally equipped with high-resolution screens, powerful processing units, and inbuilt GPS, accelerometers, and gyroscopes that provide accurate tracking and positioning, it is unsurprising

Table 1 Summary description of studies included in the systematic review

	References	Research Objective	Method (sample size)	Display Device	Environment	Localization	Visualization
1	Stigall et al. (2019)	Use of Microsoft HoloLens for navigational assistance in evacuation scenarios	Mixed method (10)	HMD	Indoor	Marker	Map
2	Rochadiani et al. (2022)	Navigating through a shopping mall environment using augmented reality	Mixed method (20)	Mobile	Indoor	SLAM	Map
3	Ahmad et al. (2005)	Gender differences in navigation and wayfinding using mobile augmented reality	Quantitative (136)	HMD	Indoor	Marker	Map
4	Kim et al. (2015)	User experiences with an augmented reality-enabled wayfinding system in complex environments	Qualitative (10)	Mobile	Indoor	Marker	TBT
5	Smith et al. (2017)	Using augmented reality to improve navigation skills in postsecondary students with intellectual disability	Mixed method (3)	Mobile	Outdoor	GPS	TBT, map
6	Ping et al. (2020)	Applying a mobile AR guide system to enhance user experience in cultural heritage sites	Mixed method (24)	Mobile	Outdoor	GPS	POI
7	Hou and Tang (2020)	Contrast and parameter research for an augmented reality indoor navigation scheme	Mixed method (24)	Mobile	Indoor	SLAM	TBT, map
8	Arntz et al. (2020)	Navigating a heavy industry environment using augmented reality, comparing two types of AR designs	Mixed method (52)	HMD	Indoor	SLAM	TBT
9	Romli et al. (2020)	Mobile augmented reality marker-based approach for indoor library navigation	Mixed method (20)	Mobile	Indoor	Marker	TBT, POI
10	Drewlow et al. (2022)	Use of augmented reality to improve navigation in a hospital environment	Mixed method (12)	Mobile	Indoor	SLAM	TBT
11	Sheoprashad and Defreitas (2022)	Investigating indoor navigational experiences with a mobile augmented reality prototype versus conventional methods	Mixed method (10)	Mobile	Indoor	SLAM	TBT
12	Wakchaure et al. (2022)	Indoor navigation system for public evacuation in emergency situations	Mixed method (3)	Mobile	Indoor	Marker	TBT
13	Yunardi et al. (2022)	Design and development of an object-detection system in AR for indoor navigation	Quantitative (20)	Mobile	Indoor	SLAM	TBT, POI
14	Sharin et al. (2023)	Combining a step-counting technique with augmented reality for a mobile-based indoor localization	Mixed method (4)	Mobile	Indoor	Marker	TBT
15	Kluge and Asche (2012)	Validating a smartphone-based pedestrian navigation system prototype with eye-tracking	Mixed method (3)	Mobile	Outdoor	GPS	TBT, map
16	Schougaard et al. (2012)	Indoor pedestrian navigation based on hybrid route planning and location modeling	Mixed method (1)	Mobile	Indoor	SLAM	TBT, map
17	Rehrl et al. (2014)	Field study evaluating pedestrian navigation with augmented reality, voice instructions, and a digital map	Mixed method (24)	Mobile	Outdoor	GPS	TBT, map
18	Rovelo et al. (2015)	Studying the user experience with a multimodal pedestrian navigation assistant	Mixed method (77)	Mobile	Outdoor	GPS	TBT, map
19	Chin and Lee (2015)	Interactive indoor navigation system using visual recognition and pedestrian dead reckoning techniques	Mixed method (10)	Mobile	Indoor	SLAM	NS
20	Amirian and Basiri (2016)	Landmark-based pedestrian navigation using augmented reality and machine learning	Mixed method (20)	Tablet	Outdoor	GPS	TBT, POI
21	Brata and Liang (2020)	Comparative study of user experience between a digital map interface and location-based augmented reality	Mixed method (10)	Mobile	Outdoor	GPS	TBT, POI
22	Tang and Zhou (2020)	Usability assessment of an augmented reality-based pedestrian navigation aid	Mixed method (28)	Mobile	Outdoor	GPS	TBT, map, avatar
23	Anbaroglu et al. (2020)	Comparison of augmented reality vs. a paper map for pedestrian wayfinding outcomes	Mixed method (33)	Mobile	Outdoor	GPS	TBT, map
24	Ng and Lim (2020)	Design of a mobile augmented reality-based indoor navigation system	Mixed method (10)	Mobile	Indoor	SLAM	TBT, avatar, POI
25	Lee et al. (2020)	Use of AR to help in locating specific books in a library environment	Mixed method (60)	Mobile	Indoor	SLAM	TBT, POI

Table 1 (continued)

	References	Research Objective	Method (sample size)	Display Device	Environment	Localization	Visualization
26	Kamalam et al. (2022)	Augmented reality navigation for wearable devices with machine-learning techniques	Mixed method (2)	Mobile	Indoor	SLAM	TBT
27	Preethaet al. (2023)	Design and implementation of an augmented reality mobile application for finding bank ATMs	Mixed method (100)	Mobile	Outdoor, Indoor	GPS, SLAM	POI
28	Gerstweiler et al. (2017)	Development and testing of a dynamic AR guiding system for indoor environments	Mixed method (28)	HMD	Indoor	SLAM	TBT
29	Mohd Nizam et al. (2021)	Indoor navigation support for the student halls of residence using augmented reality	Mixed method (71)	Mobile	Indoor	Marker	TBT, map
30	Kasprzak et al. (2013)	Evaluation of feature-based indoor navigation using augmented reality	Mixed method (17)	Mobile	Indoor	Marker	TBT
31	Rubio-Sandoval et al. (2021)	An indoor navigation method for mobile devices by integrating augmented reality with the Semantic Web	Mixed method (24)	Mobile	Indoor	Marker	TBT, map
32	Calle-Bustos et al. (2021)	Evaluating visual vs. auditory cues in AR for indoor guidance	Mixed method (20)	Mobile	Indoor	SLAM	TBT
33	Zhang and Nakajima (2020)	Gamified AR navigational system to prompt residents to explore new areas of a city	Mixed method (5)	Mobile	Outdoor	GPS	TBT, avatar
34	Joo-Nagata et al. (2017)	Augmented reality and pedestrian navigation in the context of an educational program in Chile	Mixed method (143)	Mobile	Outdoor	GPS	Map, POI
35	Montuwy et al. (2019)	Effectiveness and UX for older adults using sensory wearable devices to navigate an urban environment	Mixed method (18)	HMD	Outdoor	GPS	TBT
36	Huang et al. (2012)	Spatial knowledge acquisition with mobile maps, augmented reality, and voice instructions	Mixed method (24)	Mobile	Outdoor	GPS	TBT, map
37	San Martin and Kildal (2021)	Audio-visual mixed reality representation of hazard zones for safe pedestrian navigation	Mixed method (12)	HMD	Indoor	NS	TBT
38	Chaturvedi et al. (2019)	Evaluating a novel AR application for enhancing pedestrian's peripheral vision	Mixed method (12)	HMD	Outdoor, Indoor	GPS, NS	TBT
39	Ajmi et al. (2019)	Development and evaluation of an AR system to assist people with motor disabilities	Mixed method (20)	HMD	Outdoor	GPS	Map, POI
40	Makimura et al. (2019)	Visual effects of turning point and travel direction for outdoor navigation using a head-mounted display	Quantitative (16)	HMD	Outdoor	NS	TBT
41	Rehman and Cao (2017)	Comparing handheld AR devices versus Google Glass for indoor navigation	Mixed method (39)	HMD, Mobile	Indoor	SLAM	TBT
42	McKendrick et al. (2016)	Neuroergonomic differentiation of hand-held and AR wearable displays during outdoor navigation	Mixed method (20)	HMD	Outdoor	NS	Map
43	Lee (2022)	Benefit analysis of a gamified augmented reality navigation system	Quantitative (99)	Mobile	Outdoor	Marker	Map, avatar
44	Debandi et al. (2018)	Enhancing cultural tourism by a mixed reality application for outdoor navigation and information browsing	Qualitative (8)	HMD	Outdoor	NS	POI
45	Lu et al. (2021)	Use of AR for enhancing navigation in a university campus environment	Mixed method (120)	Mobile	Outdoor, Indoor	GPS, SLAM	TBT, map
46	Araujo et al. (2019)	Improving fluid transitions between environments in mobile augmented reality applications	Mixed method (11)	Mobile	Outdoor, Indoor	GPS, SLAM	TBT, map, POI
47	Nenna et al. (2021)	Using AR to investigate cognitive–motor tasks during outdoor navigation	Mixed method (45)	HMD	Outdoor	NS	POI
48	Dunser et al. (2012)	Evaluating the use of handheld AR during outdoor navigation	Mixed method (22)	Mobile	Outdoor	GPS	TBT, map
49	Liu et al. (2021)	Spatial knowledge acquisition with virtual semantic landmarks in mixed reality-based indoor navigation	Mixed method (28)	HMD	Indoor	SLAM	TBT, POI
50	Kuwahara et al. (2019)	Evaluation of a campus navigation application using an AR character guide	Mixed method (16)	Mobile	Indoor	Marker	TBT, avatar

Table 1 (continued)

	References	Research Objective	Method (sample size)	Display Device	Environment	Localization	Visualization
51	Torres-Sospedra et al. (2015)	Enhancing integrated indoor/outdoor mobility on a "smart campus."	Quantitative (150)	Mobile	Outdoor	GPS	TBT, POI
52	Huang et al. (2019)	An augmented reality sign-reading assistant for users with reduced vision	Mixed method (24)	HMD	Indoor	SLAM	POI
53	Munoz-Montoya et al. (2019)	Evaluating the use of AR to assist in object location, including the role of gender	Mixed method (46)	Mobile	Indoor	SLAM	POI
54	Sekhavat and Parsons (2018)	The effect of different AR tracking techniques on the quality of user experience	Mixed method (90)	Mobile	Indoor	SLAM, Marker	TBT, map, POI
55	Zhao et al. (2020)	The effectiveness of visual and audio wayfinding guidance on smartglasses for people with low vision	Mixed method (16)	HMD	Indoor	SLAM	TBT
56	Truong-Allié et al. (2021)	Use of adaptive AR guidance for wayfinding and task completion	Mixed method (28)	HMD	Indoor	SLAM	TBT
57	Goldiez et al. (2007)	Effects of augmented reality display settings on human wayfinding performance	Quantitative (120)	HMD	Indoor	Marker	Map
58	Dong et al. (2021)	Evaluating augmented reality vs. 2D navigation for pedestrian wayfinding	Mixed method (73)	Mobile	Outdoor	GPS	TBT
59	Zhang et al. (2021)	Enhancing human indoor cognitive map development and wayfinding performance with AR navigation systems	Mixed method (54)	HMD	Indoor	Marker	TBT, map
60	Mulloni et al. (2011b)	User experiences of AR navigational support delivered via smart-phones	Mixed method (9)	Mobile	Outdoor	NS	TBT, map
61	Xie et al. (2022)	Using AR maps to support volunteers in navigating unfamiliar environments	Mixed method (13)	Tablet	Indoor	SLAM	Map
62	Mulloni et al. (2012)	Indoor navigation with mixed reality world-in-miniature views and sparse localization on mobile devices	Mixed method (8)	Mobile	Indoor	Marker	TBT, map
63	Mulloni et al. (2011a)	Handheld augmented reality indoor navigation with activity-based instructions	Mixed method (10)	Mobile	Indoor	Marker	TBT, map
64	Kerr et al. (2011)	User experiences of wearable mobile augmented reality for outdoor navigation	Qualitative (8)	HMD	Outdoor	GPS	TBT, map
65	Möller et al. (2014)	Evaluation of different types of AR interfaces for visual indoor navigation	Mixed method (12)	Mobile	Indoor	SLAM	TBT
66	Qiu et al. (2024b)	A landmark-based AR wayfinding system for enhancing older adults' spatial learning	Mixed method (32)	HMD	Indoor	SLAM	TBT, POI
67	Valizadeh et al. (2024)	Indoor AR pedestrian navigation for emergency evacuation based on BIM and GIS	Mixed method (21)	Mobile	Indoor	SLAM	TBT
68	Lakehal et al. (2023)	Spatial knowledge acquisition for pedestrian navigation between smartphones and AR glasses	Mixed method (20)	HMD	Outdoor	GPS	TBT, POI
69	Xu et al. (2024)	Improving indoor wayfinding with AR-enabled egocentric cues	Mixed method (31)	HMD	Indoor	SLAM	Map
70	Fajrianti et al. (2023)	Indoor navigation system using Unity and smartphone for user ambulation assistance	Quantitative (30)	Mobile	Indoor	Marker	TBT, map
71	Pesaladinne et al. (2023)	Situational awareness and feature extraction for indoor building navigation using mixed reality	Quantitative (10)	HMD	Indoor	Marker	Map
72	Qiu et al. (2024a)	Impact of AR navigation display methods on wayfinding performance and spatial knowledge acquisition	Mixed method (20)	Mobile	Outdoor	GPS	TBT, POI
73	Xie and Seals (2023)	Design of mobile AR application via deep learning and LIDAR for visually impaired	Quantitative (20)	HMD	Indoor	SLAM	TBT
74	Truong-Allié et al. (2023)	Influence of AR on perception, comprehension and projection levels of situation awareness	Mixed method (10)	Mobile	Indoor	SLAM	TBT
75	Bibbò et al. (2024)	AR indoor navigation platform for older people with cognitive impairment	Quantitative (7)	Mobile	Indoor	SLAM	TBT

Table 1 (continued)

	References	Research Objective	Method (sample size)	Display Device	Environment	Localization	Visualization
76	Romli et al. (2024)	AR for indoor positioning and navigation apps	Quantitative (10)	Mobile	Indoor	SLAM	TBT, POI, map
77	Nendya et al. (2023)	AR indoor navigation using NavMesh	Quantitative (7)	Mobile	Indoor	Marker	TBT, POI
78	Qi et al. (2024)	AR campus navigation for both indoor and outdoor spaces based on ARCore	Quantitative (120)	Mobile	Outdoor, Indoor	GPS, SLAM	TBT, map
79	Bide et al. (2023)	AR indoor navigation with smart appliance control	Quantitative (NS)	Mobile	Indoor	SLAM	TBT
80	Sundarramurthi et al. (2023)	AR navigation system for seamless integrate for both indoors and outdoors	Quantitative (40)	Mobile	Indoor	SLAM	TBT
81	Maran et al. (2023)	AR-based indoor navigation using Unity Engine	Quantitative (5)	Mobile	Indoor	SLAM	TBT, POI
82	Harwati et al. (2024)	System usability evaluation of AR indoor navigation	Quantitative (50)	Mobile	Indoor	Marker	TBT, POI, map
83	Sharma (2023)	Mobile AR system for emergency response	Quantitative (10)	Mobile	Indoor	Marker	POI, map
84	Achmad et al. (2024)	AR navigation for indoor and outdoor environments	Quantitative (32)	Mobile	Outdoor, Indoor	GPS, Marker	TBT
85	Safranoglou et al. (2024)	AR for real-time decision-making in flood emergencies	Mixed method (NS)	HMD	Outdoor	GPS	POI, map
86	Kumaran et al. (2023)	The impact of navigation aids on search performance and object recall in wide-area AR	Mixed method (24)	HMD	Outdoor	SLAM	TBT, map
87	Park et al. (2024)	Comfortable mobility or attractive scenery for outdoor AR storytelling	Mixed method (35)	Mobile	Outdoor	GPS	TBT, POI, map
88	Mazurkiewicz et al. (2023)	AR beeline navigation for spatial knowledge acquisition	Mixed method (48)	HMD	Outdoor	GPS	POI

NS: Not specified. TBT: Turn-by-turn instructions that includes path visualization, action signs, and/or distance. Map: Overview 2D/3D map. POI: Point-of-interest or location-based information

that such devices played a prominent role in the research literature. However, in recent years transparent HMDs ("smart glasses") have become more widely available and are beginning to occupy a larger share of AR projects. These displays provide a hands-free experience by incorporating sensors and cameras directly in the headset for environmental scanning and user interaction. They can also provide sophisticated audio components to enhance the user's sense of immersion. The papers that we reviewed included 19 using Microsoft HoloLens, 4 using Google Glasses, and 7 using custom-designed HMDs. This latter group is particularly notable, as early adopters such as Kerr et al. (2011) designed their own head-mounted systems, a process that helped to spur the technology's development and contributed to today's more sophisticated smart-glasses systems (Makimura et al. 2019; Truong-Allié et al. 2021).

4.1.2 Software solutions

The choice of development platforms is essential for integrating software development kits (SDKs) and application programming interfaces (APIs) to develop AR applications across various devices. Among 54 studies that specified their development platforms, Unity (Unity Technologies 2025) was the most popular, being used in 34 studies. An additional 15 studies opted for custom-designed platforms, while the remaining 15 used diverse commercial platforms such as Android Studio (Android Studio, 2025). Regarding SDKs, 18 studies used the Vuforia Engine (Vuforia Engine 2025), 5 used ARCore (Google LLC 2025), 4 used ARKit (Apple Inc., 2025), 1 used the Mixed Reality Toolkit (Mirosoft Corporationc MRTK, 2025), and 6 used custom-developed SDKs. The remaining studies did not report their SDKs. Some of the custom-developed AR technologies in these studies were quite impressive; for example, Truong-Allié et al. (2021) developed a task-based neural network architecture designed to detect and classify user behaviors, such as local tasks, menu interactions, and visual searches, and to display AR guidance correspondingly. It is worth noting that all studies conducted before 2015 exclusively used custom platforms, with a noticeable shift towards the Unity and Vuforia Engines since 2018.

4.1.3 Localization techniques

The importance of localizing and tracking techniques in AR pedestrian navigation applications cannot be overstated, as they provide the precise positioning necessary to successfully maintain alignment between the virtual components and the physical environment. In our review, all of the studies that were focused on outdoor navigation and that reported their localization techniques (n = 27) used GPS as an exclusive approach. The indoor studies exhibited more diversity in their approaches (Table 1). A marker-based technique was featured in 22 of the articles on indoor navigation, meaning that QR codes or other location markers were placed within the environment to be recognized by a camera on the user's mobile device (Fig. 2). Mulloni and colleagues' study (2011a) exemplified this technique, using floor-mounted fiduciary markers at selected indoor locations. Upon detecting a marker, the app would automatically update its action-based instructions, providing current location, map orientation, and directions to the destination. A more recent study by Rubio-Sandoval et al. (2021) combined QR code scanning and pose tracking, the former to establish the users' general position and the latter for fine-grained user location updates within a Unity3D coordinate system.

SLAM was used in 35 of the reviewed indoor studies. In this approach, maps are created and updated using a computational method that also tracks the location of an agent (Durrant-Whyte and Bailey 2006). The SLAM studies were further divided into 18 that used a computer-vision approach, 10 that used the features of Microsoft HoloLens, and 7 that used other scanning approaches such as Light Detection and Ranging (LiDAR). The computer vision approach employs cameras and image processing techniques to track feature points across frames for localization. One prominent study in this category was conducted by Huang et al. (2019), who used optical character recognition for text-based sign identification. Among the novel localization approaches found, Xie et al. (2022) and Xie and Seals (2023) built a 3D environmental map using a LiDAR scanner and then employed the iOS's ARKit features to display the user's location and orientation within this map.

4.1.4 Pathfinding techniques

Creating paths is crucial for rendering navigational aids in AR by determining optimal routes. Out of 61 articles that clearly identified their pathfinding techniques, 38 depended on predetermined paths for navigation tasks. This prevalence could be attributed to the specific research objectives requiring participants to adhere to particular wayfinding tasks. For instance, Montuwy et al. (2019) used AR glasses to present predefined, turn-by-turn directions at intersections to navigate users, whereas Kim et al. (2015) employed markers to signify turn points, guiding users from one marker to the next. Conversely, 23 of the reviewed articles employed real-time path generation algorithms. For example, Rubio-Sandoval et al. (2021) applied Dijkstra's algorithm to determine the shortest path, considering adjacency and array of nodes in matrices that represented the spatial model. Gerstweiler et al. (2017) introduced the FOVPath algorithm, which initially used the A* algorithm to draft a basic path. This was subsequently refined by the Middle Path concept, optimizing navigational guidance based on the user's field of view, allowing for precise path modifications in the immediate surroundings.

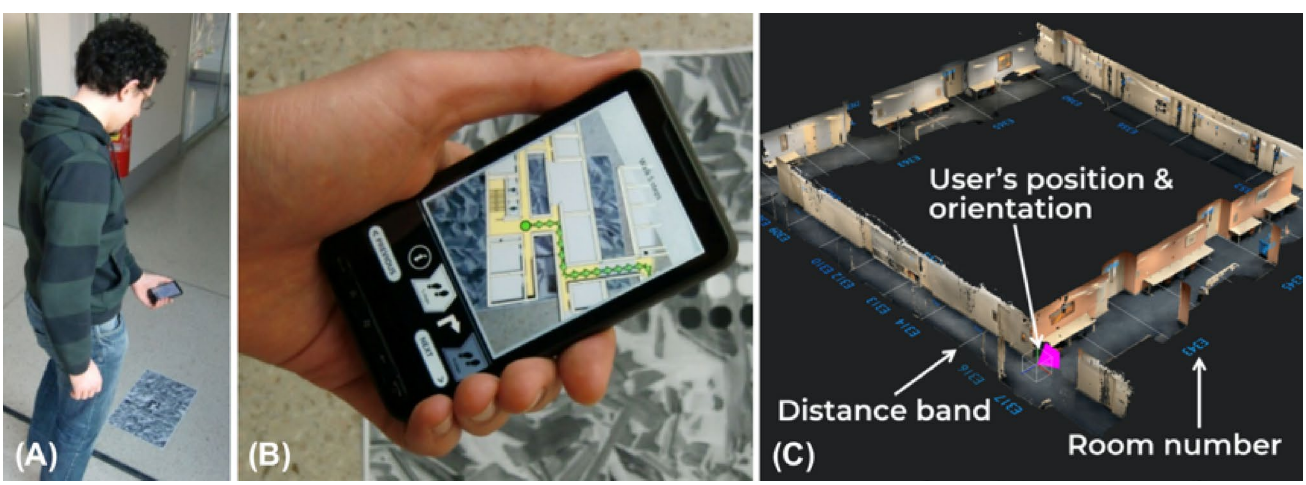

Fig. 2 Example of marker-based AR systems: **A** Markers are placed in the physical environment, in this case on the floor; **B** The smartphone app is activated by scanning the markers, in this case on the floor; and **C** The AR system can track user's real-time position and orientation (Mulloni et al. 2011a; Xie et al. 2022)

4.1.5 Visualization techniques and user interfaces

Efficient user interfaces are crucial in AR, representing a significant departure from conventional wayfinding applications that limit users to a two-dimensional map view. When information is being overlayed onto the physical environment, it is important not to create too many distractions, so these virtual elements are usually designed in a streamlined fashion. Most of the studies we reviewed combined at least two visualization techniques, including path visualization (35 studies), the use of an auxiliary map (29 studies), action-based instructions or arrows (26 studies), and displays of distance to a destination or turning point (23 studies) (Figs. 3 and 4).

Dong et al. (2021), for example, used an AR module to overlay a blue-colored path onto the camera view, alongside screen-fixed turn arrows indicating the path to the destination. Kim et al. (2015) proposed a system featuring multiple real-time-updated arrows to indicate direction and distance to destinations on a smartphone, with additional destination-related information provided via floating virtual tags. Some researchers enhanced the navigation process by overlaying a 2D map onto the path and supplementing it with additional landmark information. For example, the system proposed by Oliveira de Araujo et al. (2019) featured an AR browser for outdoor navigation with a hierarchical location display, a simple point-of-interest (POI) search function, a mini radar indicating surrounding POIs, and virtual markers for route guidance. When changing to indoor navigation, their system display adjusted to present location details and building floor plans, while adopting image recognition for localization. Similar multi-functional interfaces were also developed by Sekhavat and Parsons (2018) and by Qiu et al. (2024b).

Some of the studies in our review integrated virtual avatars, interactive quizzes, and other novel visualization techniques into their AR systems to promote user engagement. An example of this is the “BearNavi” app developed by Kuwahara et al. (2019), which used a university’s bear mascot avatar to guide users around campus while engaging them in educational activities. Similarly, Lee (2022) developed a system in which users followed a virtual AR guide throughout an exhibition, scanning artwork labels for information and amassing virtual souvenirs. Chaturvedi et al. (2019) devised a peripheral vision model for smartglasses, which enables users to assimilate information via color and motion detection around the edge of the visual area without shifting their visual focus away from their primary activity.

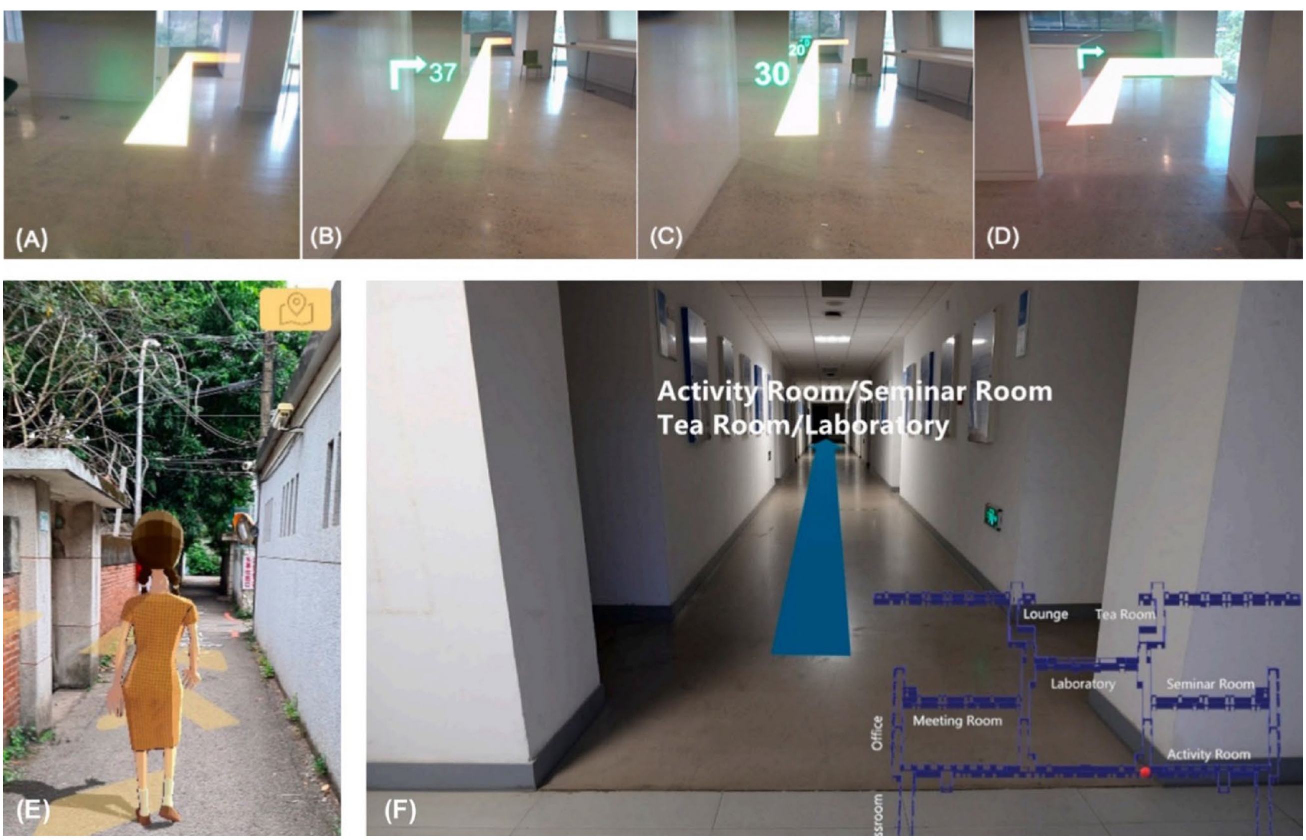

Fig. 3 Example of different types of visual wayfinding guidance: **A** Visual display of path; **B** Path with floating directional window; **C** Path with multiple anchored signs; **D** Single anchored directional sign; **E** Avatar guide; **F** Path display with integrated map (Lee 2022; Zhang et al. 2021; Zhao et al. 2020)

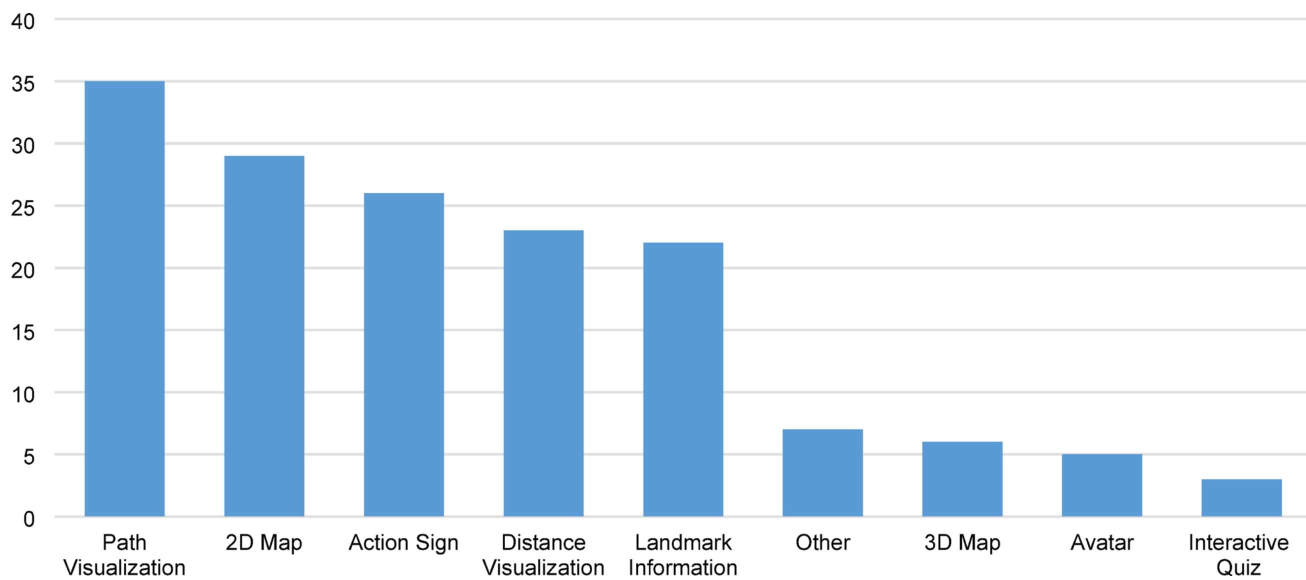

Fig. 4 Types of visualization techniques used in the reviewed literature

4.2 Factors related to user experience and the acceptance of AR technologies (RQ2)

We identified 71 studies that examined the user experience (UX) of AR navigational assistance systems. These were classified into five distinct categories based on the measurement constructs that they employed (Table 2), including Overall Usability (58 studies), Attitude (25 studies), Perception (16 studies), Acceptance (9 studies), and Immersiveness and Presence (8 studies). Some studies fell into multiple categories and were therefore counted in each. Regarding the display technologies used in these studies, 49 employed handheld devices and 22 employed HMDs. The methods for evaluating UX varied widely across the studies: 46 exclusively used custom questionnaires; 13 employed established system scales such as the System Usability Scale (Brooke 1986) and the Unified Theory of Acceptance and Use of Technology II Scale (Venkatesh et al. 2012); 3 evaluated user experience based on interviews; 5 employed a combination of custom questionnaires and interviews; and the remaining 4 combined custom questionnaires with existing system scales.

4.2.1 Usability

We defined usability in the context of AR navigation systems as the degree to which the technology enabled users to complete wayfinding tasks effectively, efficiently, and satisfactorily (International Organization for Standardization 1998). Many of the studies employed standardized instruments to measure usability in a broad fashion, an evaluation that can overlap with other constructs discussed below such as perception or attitude, but is not reducible to those components. Out of the 58 reviewed studies that focused on usability, 49 used comprehensive metrics to examine the overall usability, while the rest honed in on specific aspects such as ease of use, efficiency, learnability, and comfort. The majority of the studies reported that participants gave high usability ratings to AR navigational support systems. However, there were a few notable papers that highlighted usability problems. Tang and Zhou (2020) evaluated the usefulness of an AR outdoor navigation app for both older and younger adults, and found several issues including discrepancies between the included virtual map and the real environment, confusion about the meaning of instructions, abrupt changes in routes, and inaccurate tracking. Zhang et al. (2021) reported that while participants gave a HoloLens-based navigational assistance app high scores for effectiveness, they also found the technology difficult to use, particularly when trying to scan for QR code-based markers. Therefore, while AR navigation systems show promising usability overall, the specific design of these systems needs to be carefully evaluated to identify and overcome any emerging usability challenges for the targeted population.

4.2.2 Acceptance

Only 9 studies in our review evaluated metrics of technology acceptance, which refers to the willingness of participants to adopt AR for regular use. Of these, 6 examined overall acceptance, while 3 evaluated various constellations of related constructs such as perceived usefulness and learnability. The findings of all studies in this area were consistently positive. Kasprzak et al. (2013), for example, demonstrated that participants preferred to use an AR-based navigation support system for locating destinations,

Table 2 Constructs employed to evaluate user experience in the reviewed literature

Main Categories	Subcategories	Number of Studies per Subcategory	Example References
Usability	Comprehensive (efficiency, effectiveness, satisfaction, ease of use, learnability, usefulness, comfort)	49	Mulloni et al. (2011a), Torres-Sospedra et al. (2015), Drewlow et al. (2022)
Acceptance	Efficiency	3	Xie et al. (2022)
	Ease of use	2	Möller et al. (2014)
	Comfort	2	Truong-Allié et al. (2021)
	Learnability	1	Ping et al. (2020)
	Perceived usefulness	3	Debandi et al. (2018), Montuwy et al. (2019)
	Comprehensive (perceived ease of use, perceived usefulness)	5	Arntz et al. (2020), Zhang et al. (2021)
Attitude	Preference	23	Anbaroglu et al. (2020), Dunser et al. (2012), Zhao et al. (2020)
	Comprehensive (preference, frustration, trust, confidence, aesthetics, pleasantness)	2	Lu et al. (2021)
Perception	Frustration	3	Kasprzak et al. (2013)
	Confidence	3	Joo-Nagata et al. (2017)
	Pleasantness	1	San Martin and Kildal (2021)
	Understanding of virtual guidance	5	Möller et al. (2014), Oliveira de Araujo et al. (2019)
	Comprehensive (understanding of guidance, situation awareness)	8	Kuwahara et al. (2019), Qiu et al. (2024b)
Immersiveness and Presence	Situational awareness	5	Sekhavat and Parsons (2018), Truong-Allié et al. (2023)
	Interactivity	3	Kerr et al. (2011), Zhang and Nakajima (2020)
	Immersion	1	Hou and Tang (2020)
	Comprehensive (interactivity, immersiveness)	1	Ping et al. (2020)

compared to seeking out real-world information points or asking other people. Similarly, Debandi et al. (2018) developed an application that provided navigational support along with additional information about historical buildings through an HMD. Their study found that users were highly accepting of the technology and viewed it as beneficial. Dunser et al. (2012) compared user acceptance between a handheld AR device, a digital map, and a combined condition involving both AR and a digital map. They found that users rated the AR condition highly but preferred the combined interface.

4.2.3 Attitude

Attitude towards AR navigation support systems, which is defined as a user's positive or negative feelings about interacting with the technology (Fishbein and Ajzen 1975), was examined in 21 studies. Our review indicated that participants tended to exhibit a strong preference for AR navigation over traditional methods, and that they tended to favor visual AR modalities over auditory information. For example, Calle-Bustos et al. (2021) found that participants reported more positive attitudes toward visual AR feedback compared to audio, and that they cited enhanced entertainment value and reduced attention requirements when explaining this preference. Lu et al. (2021) found that participants had more positive attitudes toward immersive 3D map displays compared to 2D AR maps. When compared against the use of physical signs for navigation, AR consistency elicited more positive attitudes—for example, Huang et al. (2019) created a sign-reading app capable of identifying real-world text and highlighting it in AR, and found that users had more positive attitudes toward the AR navigation when it was compared directly against non-aided navigation experiences.

4.2.4 Perception

Perception in the realm of AR refers to a user's subjective assessment of how well they can see virtual navigation instructions such as turn-arrows and virtual markers, as well as their simultaneous awareness of situational information in the real-world environment. Of the 16 studies in our review that measured related constructs, 8 explored overall perception, 5 focused on the understanding of virtual cues, and 3 evaluated situational awareness. The vast majority of this literature reported that participants had a clear perception of the AR and physical elements. Sekhavat and Parsons (2018), for example, developed an AR system that provided both navigational instructions and point-of-interest textual descriptions, and found that users had no difficulties perceiving and understanding both types of information.

Intriguingly, Kuwahara et al. (2019) studied user perceptions of an AR avatar used for route guidance, and discovered that the inclusion of this character increased user's reported perception of environmental information. However, Montuwy et al. (2019) noted that some participants struggled to perceive navigational instructions provided in a smartglasses app, and concluded that the weak intensity and short duration of the guidance contributed to these problems.

4.2.5 Immersiveness and presence

Only a few studies (n = 8) in our review evaluated levels of immersion and/or presence. The reasons for this dearth in the literature are not entirely clear, but it may be the case that these constructs are associated more with fully artificial VR environments and less often occur to AR researchers to consider them. One notable related study in our review was conducted by Ping et al. (2020), who designed an outdoor navigational support system for a cultural heritage site that also enabled users to interact with virtual historical characters and engage in puzzle games associated with various POIs. When evaluating this AR system, the researchers found that participants who used it reported higher engagement and immersion levels and had greater subsequent content understanding compared to a non-AR group. Similarly, Zhang and Nakajima (2020) created a gamified navigation guide for city exploration that included interactive storyline activities at POIs. Participants in the study reported that the interactive elements increased their sense of engagement with the destinations and enriched their recollections of the environment.

4.3 Effects of AR navigational assistance on human wayfinding performance (RQ 3)

A total of 35 empirical studies were found that used comparative measurements of wayfinding performance. Of these studies, 20 compared AR against non-AR conditions, while 15 compared between different AR modalities or evaluated other potentially moderating variables such as gender (Table 3). The experiment settings also varied, with 21 studies conducted in indoor environments, 13 in outdoor environments, and 1 using both indoor and outdoor environments. In relation to the AR display method used, 20 of these studies employed handheld devices (smartphones and/or tablets), and 15 employed HMDs. The objective measures of wayfinding performance most frequently used were the task completion time and the number of errors committed. Additional domain-specific measures were also represented in various studies, such as the number of stops/pauses, the number of steps taken, the length of deviation from shortest path, and the participants' walking speed.

Notably, fifteen (75%) of the studies that compared AR-supported navigation against traditional guidance methods, such as paper maps or existing physical signage, observed superior wayfinding performance in the AR condition, as measured by reduced task completion times and/or fewer navigational errors. For example, Zhang et al. (2021) tasked participants with indoor wayfinding tasks either using an AR navigation-support system through the HoloLens, or without such assistance. The findings indicated that the AR assistance significantly reduced average wayfinding time, incorrect path length, number of incorrect decisions, and number of pauses. Similarly, Qiu et al. (2024a) reported a significant reduction in task completion times in outdoor environment when using handheld AR devices as compared to paper maps. The five studies in our review that did not observe superior wayfinding performance when using AR were all inconclusive; that is, they found no significant differences in the AR vs. non-AR conditions. The reasons for this are unclear and it may be that the data was not extensive enough to confirm fine-grained statistical differences. Rehrl et al. (2014) argued, however, that the AR navigational system that they evaluated might be inferior to a GPS-enhanced digital map and to a voice-only guidance system.

Four studies in our review used performance measures to evaluate the integration of interactive maps into AR systems. Generally, there was a positive correlation between the adoption of map interfaces and improved wayfinding performance. In a study conducted by Hou and Tang (2020), the integration of a 2D layout map into the AR interface resulted in participants completing navigation tasks faster and with fewer steps taken. Mulloni et al. (2011a) combined action-based instructions with a 3D layout map at selected information points in an indoor environment, and found that the addition of the map enhanced wayfinding task performance. Conversely, however, Tang and Zhou (2020) found no significant differences in navigation errors and walking speed when adding 2D maps to an AR interface alongside path visualizations. Xie et al. (2022) compared the use 3D vs. 2D maps in an indoor AR system for visually impaired participants, and found that using the 3D maps reduced wayfinding task completion time.

An additional five studies in the review compared different AR guidance modalities, including visual, auditory, and tactile. Three of these studies found visual guidance to be superior at enhancing wayfinding performance, with one study finding no significant differences. Zhao et al. (2020) developed a visual and audio wayfinding guidance system using an HMD, and found that participants made fewer errors and had faster task completion time when using the visual guidance, even for some participants who had partial vision impairments. Similarly, Calle-Bustos et al. (2021) reported more deviation steps take by participants when

Table 3 Studies in the review that compared wayfinding performance

Framework	Study Result	References	Comparison	Dependent Measures	Setting
AR vs. Non-AR	AR higher performance	Anbaroglu et al. (2020)	Handheld to paper map	Task completion time	Outdoor
		Goldiez et al. (2007)	HMD to paper map	Task completion time	Indoor
		Huang et al. (2019)	AR signs to no guidance	Extra distance ratio, walking speed, task duration	Indoor
		Kasprzak et al. (2013)	Handheld to paper map	Task completion time, wrong turns and pauses	Indoor
		Montuwy et al. (2019)	HMD to digital map	Time to destination, number of errors	Outdoor
		Lee et al. (2020)	Handheld to text signs	Task completion time, distance travelled	Indoor
		Rehman and Cao (2017)	HMD and handheld to paper map	Task completion time, route retention error	Indoor
		Rubio-Sandoval et al. (2021)	Handheld to no guidance	Navigation time	Indoor
		Smith et al. (2017)	AR to no guidance	Number of waypoint decisions made	Outdoor
		Zhang et al. (2021)	HMD to no guidance	Wayfinding time, extra path length, number of incorrect decisions, number of pauses	Indoor
		Kumaran et al. (2023)	HMD to no guidance	Task completion time	Indoor
		Mazurkiewicz et al. (2023)	HMD to digital map	Task completion time, distance travelled	Outdoor
		Truong-Allié et al. (2023)	HMD to no guidance	Distance travelled	Indoor
		Qiu et al. (2024a)	Mobile to digital map	Task completion time, distance trav-elled, speed	Outdoor
		Qiu et al. (2024b)	HMD to no guidance	Task completion time, distance travelled	Indoor
	No difference	Dong et al. (2021)	Handheld to digital map	Wayfinding duration, frequency of mistakes or hesitation events	Outdoor
		Dunser et al. (2012)	Handheld to digital map	Time to navigate between locations, distance travelled	Outdoor
		Huang et al. (2012)	Handheld to digital map and voice guidance	Completion time, number of stops	Outdoor
		Lee (2022)	Handheld to 2D map	Distance travelled, travel time	Outdoor
		Rehrl et al. (2014)	Handheld to digital map and voice guidance	Completion time, number and duration of stops	Outdoor
AR vs. AR	Map higher performance	Hou and Tang (2020)	2D map to no map	Task completion time, step deviation	Indoor
		Mulloni et al. (2011a)	3D map to no map	Step difference, task completion time, navigation errors	Indoor
		Xie et al. (2022)	3D map to 2D map	Task completion time	Indoor
	No difference for map	Tang and Zhou (2020)	2D map to no map	Success rate, navigation error, speed variation	Outdoor
	Visual higher performance	Calle-Bustos et al. (2021)	Visual to audio guidance	Task completion time	Indoor
		Rovelo et al. (2015)	Visual to tactile guidance	Task completion time, number of errors	Outdoor
		Zhao et al. (2020)	Visual to audio guidance	Navigation time, error rates	Indoor
	No difference for visual	San Martin and Kildal (2021)	Visual to audio and audiovisual	Task completion time	Indoor
	Egocentric visual had higher performance	Xu et al. (2024)	HMD egocentric to exocentric	Task completion time, speed	Indoor
Moderating/ Confounding Variables	Less attention load had higher performance	Nenna et al. (2021)	Single task to dual task	Exploration time, walking velocity	Outdoor
	Location-based AR had higher performance	Sekhavat and Parsons (2018)	Location-based AR to marker-based AR	Completion time, error counts	Indoor/ outdoor
	Male had higher performance	Ahmad et al. (2005)	Female to male	Task completion time, percentage of maze covered	Indoor

Table 3 (continued)

Framework	Study Result	References	Comparison	Dependent Measures	Setting
	Minimal UI had higher performance	Truong-Allié et al. (2021)	Minimal UI to complex UI	Task completion time	Indoor
	Navigation path had higher performance	Arntz et al. (2020)	Navigation path to arrow guidance	Path length, path time	Indoor
	AR video had higher performance	Möller et al. (2014)	AR video to handheld	Task completion time	Indoor

using auditory guidance on smartphones compared to visual guidance. Rovelo et al. (2015) found improved wayfinding performance when using visual feedback via an HMD compared against audio and tactile feedback (with the latter provided by a smartwatch that vibrated to indicate directional guidance). Xu et al. (2024) found that employing AR-enabled egocentric cues with comprehensive visualizations such as point clouds, floor plans, and targets significantly enhanced wayfinding and spatial awareness compared to exocentric perspectives that only displayed the route.

Finally, six studies in our review controlled the AR modality while examining moderating or confounding variables affecting performance. One study in this group reported superior wayfinding task completion times and less distance traveled for male participants than female participants when using AR guidance (Ahmad et al. 2005). Two different visual interface designs were compared by Arntz et al. (2020), who found that navigational arrows were more effective than path visualizations for improving wayfinding performance. Sekhavat & Parsons (2018) contrasted the efficacy of a marker-based localization method that utilized QR code scanning for navigation guidance, with a location-based approach that used GPS, allowing participants to explore Points of Interests (POIs) outdoors. The findings indicated that the location-based method resulted in significantly less task completion time and fewer navigation errors.

4.4 Impacts of AR navigational assistance on human perception, decision-making, behavior, and cognition (RQ4)

The review included 18 studies that examined cognitive load and cognitive map development and 6 studies that examined aspects of perception when using AR (Table 4). There were no studies found in the review that examined decision-making processes or specific wayfinding behaviors. For those focusing on cognition, 5 studies evaluated cognitive load during navigational tasks; 4 focused on the development of cognitive maps; and 9 studies examined both cognitive load and cognitive maps. Ten of these studies were conducted in indoor areas, and 8 were conducted outdoors. Various measures were employed to gauge the effect of AR on mental workload, with the NASA-TLX (Hart and Staveland 1988) being the most commonly used instrument. Other studies adopted eye tracking measures such as fixation durations, saccade amplitudes, and pupil size as real-time objective measures of cognitive load (Dong et al. 2021; Kluge and Asche 2012). One study employed wireless functional near infrared spectroscopy (fNIRS) to non-invasively monitor hemodynamic changes in the brain's prefrontal cortex as a measure of cognitive load (McKendrick et al. 2016). In addition, several studies employed a secondary cognitive task, such as a working memory test, conducted simultaneously with the wayfinding activity, and evaluated cognitive load based on the task scores. Regarding the development of cognitive maps, measurements included sketch map task, object recall task, and custom questionnaires. One study used a post-navigation wayfinding task without aids, after previous AR exploration in the building, to evaluate the establishment of cognitive maps (Zhang et al. 2021).

In 11 out of the 12 studies evaluating cognitive load (92%), the AR condition was associated with a significantly reduced mental workload compared to other navigational approaches. One notable study in this area is Zhao et al. (2020), who investigated cognitive load in relation to visual vs. audio AR guidance. Their findings indicated that participants following audio guidance had significantly greater cognitive load—which may help to explain why participants across multiple reviewed studies performed better at wayfinding when they received visual rather than audio guidance (Sect. 4.3. above). Dong et al. (2021) found that participants using AR experienced significantly lower cognitive load than those using a 2D digital map, as evidenced by eye-tracking measures. This study also found that participants using AR directed more attention towards other people in the environment. McKendrick et al. (2016) demonstrated that users of head-mounted AR exhibited significantly lower hemodynamic brain responses than those using handheld AR, indicating heightened neural activity and cognitive load in the handheld device group. The single study in our review that found worse outcomes for AR was conducted by Rehrl et al. (2014), who observed an increased cognitive load when participants navigated with a handheld AR tool compared to a combination of digital map and voice-based guidance in outdoor settings.

Table 4 Studies in the review that addressed cognition

Study Result	References	Comparison	Dependent Measures	Setting
AR lowers cognitive load	Dunser et al. (2012)	AR with 2D map to AR without map	NASA TLX	Out-door
	McKendrick et al. (2016)	HMD to mobile AR	fNIRS (functional near infrared spectroscopy)	Out-door
	Nenna et al. (2021)	Fewer AR objects to more AR objects	NASA TLX, cognitive task	Out-door
	Xie et al. (2022)	3D map to 2D map	NASA TLX	Indoor
AR lowers cognitive load but, inhibits cognitive map formation	Rehman and Cao (2017)	HMD and handheld AR to paper map	NASA TLX	Indoor
	Dong et al. (2021)	Handheld AR to paper map	Eye tracking, sketch map	Out-door
AR lowers cognitive load and enhances cognitive map formation				
	Zhang et al. (2021)	HMD to no guidance	NASA TLX, sketch map, questionnaire	Indoor
	Zhao et al. (2020)	Visual to audio guidance	Cognitive task, sketch map	Indoor
	Mazurkiewicz et al. (2023)	HMD to digital map	NASA TLX, object recall task	Out-door
	Xu et al. (2024)	HMD egocentric to exocentric	NASA TLX, situation awareness	Indoor
	Qiu et al. (2024b)	HMD to no guidance	Cognitive task, sketch map	Indoor
AR increases cognitive load	Rehrl et al. (2014)	AR system to non-AR audio guidance and mobile map	NASA TLX	Out-door
AR enhances cognitive map formation	Calle-Bustos et al. (2021)	Audio to visual	Sketch map	Indoor
	Huang et al. (2012)	Handheld to mobile map	Route memory	Out-door
	Liu et al. (2021)	HMD only	Sketch map	Indoor
	Munoz-Montoya et al. (2019)	Handheld only	Object recall task, spatial anxiety	Indoor
	Kumaran et al. (2023)	HMD to no guidance	Object recall task	Indoor
	Qiu et al. (2024a)	Handheld to digital map	Scene and orientation recall	Out-door
AR increases perception accuracy	Anbaroglu et al. (2020)	Handheld to mobile map	Questionnaire	Out-door
	Kluge and Asche (2012)	Handheld only	Eye tracking, questionnaire	Out-door
	Makimura et al. (2019)	Visual guidance only	Questionnaire	Out-door
	Möller et al. (2014)	Video to handheld	Questionnaire	Indoor
	San Martin and Kildal (2021)	Visual to audio	NASA TLX, interview	Indoor
	Truong-Allié et al. (2023)	HMD to no guidance	Situation awareness	Indoor

In regard to the development of cognitive maps, 11 out of 13 studies (85%) found that AR navigational aids significantly improved map formation. This was true across multiple types of AR content. For example, Liu et al. (2021) implemented a system featuring iconic holograms for virtual semantic landmarks, and subsequently assessed its impact on users' spatial knowledge acquisition. Their results from sketch map and landmark location tasks suggested that such virtual landmarks effectively enhanced route knowledge. Similarly, Qiu et al. (2024b) demonstrated that the combination of visual and auditory landmark information with the deployment of 3D interactive layout models in AR could substantially improve cognitive map development in indoor environments. The participants in their study maintained higher performance even after discontinuing use of the AR, compared to those who did not receive guidance. An outlier study in this area was conducted by Rehman and Cao (2017), who found that despite a reduction in cognitive workload associated with a wearable AR navigation support system, participants who used the AR had more route retention errors compared to those who used paper maps.

The 6 studies in our review that evaluated perception all focused on participants' ability to observe, integrate, and make use of the conveyed virtual information, and all of these studies found that AR enhanced perceptions of the environment. Makimura et al. (2019), for example, found that visual cues in a head-mounted display significantly enhanced perception of navigation-related elements in the environment, such as available route choices, compared to a non-AR condition. San Martin and Kildal (2021) similarly found that participants' perception of hazard zones was successfully improved by AR auditory and visual warnings about those zones. The visual information was more effective in improving the accuracy of perceived distances from the user to the hazard, while the auditory feedback was more effective in inciting a perception of danger. Another notable study in this area was conducted by Kluge and Asche (2012), who found that AR users tended to rely more on superimposed environmental information when making route decisions at intersections, while relying more on the included 2D digital map to track their position when not at decision-points.

5 Discussion

The current state-of-the-art in AR navigational support technology, as revealed in the literature review, indicates that no single type of display device, development platform, localization method, or visualization strategy has yet achieved hegemony. Handheld devices have remained one of the most common platforms for delivering AR content since their commercial debut, largely due to the widespread ownership of smartphones since the 2010s. Their prevalence in AR research and development is attributable to the integration of multiple sensors in these devices, providing a ready-to-use solution for AR systems. The expanding availability of official and third-party SDKs and platform APIs for smartphones has further simplified the development of AR applications. Handheld devices do not have a monopoly, however, and head-mounted displays account for an increasingly substantial portion of AR pedestrian navigation research in recent years. Advanced HMDs such as the HoloLens and Google Glasses have integrated technologies, including internal depth sensors and cameras, that can improve localization. Some recent studies have examined the use of LiDAR or lasers in combination with HMDs to perform environmental scanning. Similar to handheld platforms, manufacturers of HMDs have now started to provide development SDKs to facilitate application development. The presentation formats of handheld vs. HMD devices are substantially different, with implications for users' overall body positioning and freedom of movement. For example, HMDs may offer better hands-free operation suitable for high-density pedestrian navigation, while handheld devices might be preferred in scenarios where quick interaction with AR content is necessary. Thus, it is important to account for the specific device that is used when evaluating and applying research findings.

In recent years there has been a noticeable move in AR development towards all-in-one software solutions, enabling developers to create applications that can be deployed across various hardware types and operating systems. In the early 2010s, AR applications predominantly used native development tools (Dunser et al. 2012; Mulloni et al. 2011a). However, a shift towards third-party development platforms has brought together all necessary native SDKs and libraries, allowing developers to create a single AR system that can be implemented through a variety of different hardware. The Unity Engine has become the most widely used tool for application development, with SDKs such as ARKit and ARCore being employed for mobile platforms and Mixed Reality Toolkit employed for HMDs.

At the same time, user-localization techniques continue to differ widely, particularly in indoor environments. Our review found that outdoor applications typically use GPS, while indoor ones most often employ marker-based or SLAM approaches. Each method has different advantages and limitations. Marker-based localization offers great precision but requires attaching physical markers onto controlled environments. The SLAM approach allows for more flexibility but is sometimes less precise and can suffer from positional drift errors. Approaches to routing are significantly influenced by these localization methods. Technologies using marker-based approaches usually opt for predefined paths, while SLAM is more associated with computationally generated paths. The use of computational routing remains rare in current AR applications, due to its processing demands, the necessity for stable wireless connections, and reliability issues that can arise in complex multi-level environments. Nevertheless, the field appears to be moving toward the more pervasive use of computer vision and image recognition to help precisely overlay virtual elements (Delgado et al. 2020). As these techniques continue to advance, there may be opportunities to further integrate multiple localization methods into a single technology, which could enhance spatial transitions and make the AR system more flexible and scalable for use in dynamic multi-layered environments (Ng and Lim 2020).

Data visualization techniques and user interfaces have seen equally dynamic growth. The increased incorporation of multimodal interactions, including visual, auditory, and tactile cues, has provided designers and users with more options for information delivery. Visual cues have traditionally comprised turn-by-turn instructions such as path visualization, turn indicator arrows, distance indicators, action signs, and auxiliary 2D maps. However, the integration of landmark information with interactive functionalities, peripheral vision models, avatars that engage the user conversationally, and other novel techniques has led to a great diversification in AR presentations. There is still very little empirical research on the effectiveness of some of these modalities. Our evaluation of literature related to user-experience indicated that simple, streamlined visual presentations, with effective localization, tended to receive the highest user praise. As with other aspects of the technology, confounding variables make it hard to form precises and definitive conclusions on the basis of the existing research literature. However, some studies identified specific challenges and user complaints related to display devices and platform design. A frequent complaint with HMDs was headaches after prolonged use and a limited field of view that required head movements to locate the virtual content. For both handheld devices and HMDs, it was common for participants in these studies to bring up issues with overly complex or confusing interface design elements that reduced their legibility. Localization challenges were also widely noted in the literature, such as discrepancies between virtual and real routes in outdoor settings due to sun glares and other weather conditions, latency in guidance updates, and user requirements to constantly scan the environment to look for markers.

Some of the reviewed articles addressed specific pedestrian scenarios, including navigation for individuals with cognitive impairments, those with vision impairments, and emergency evacuations. For these three scenarios in particular, there is enough agreement in the literature to suggest some general guidelines. When it comes to users who have cognitive impairments, which is a broad and diverse population that includes many older adults, the overwhelming imperative is simplified interfaces with clear and easy-to-understand navigation instructions. This design consideration should outweigh the desire to integrate complex or sophisticated features if the application is intended to support cognitively impaired users. For the visually impaired, the most crucial consideration is integrating multimodal navigational cues with extensive customization. There are many different forms of visual impairment, and so these systems need to provide sufficient options in terms of visual, auditory, and tactile feedback to accommodate the circumstances and preferences of each user. The ability to process real-time environmental information, such as obstacle-awareness, is also high valuable to enhance wayfinding safety for this population.

In emergency situations, such as flooding crises or building evacuations, it is vital that AR navigation systems should be robust against environmental changes including power failures, water contact, heavy smoke, or other weather conditions. Technologies including Building Information Modeling (BIM) and pedestrian dead reckoning (PDR) are particularly useful for improving navigation accuracy in such circumstances, as they include detailed geometric data rather than only showing established paths. Interfaces oriented toward emergency situations can also benefit from precise real-time visualization of important environmental information, for example by showing areas that have become flooded or can otherwise not be traversed.

Among the most consistent findings in our review was that users disliked systems that relied purely on auditory information signals, in contrast to systems that visually highlighted physical features in the environment salient to wayfinding. It should be noted that, despite the occasional negative findings, participants in general in the reviewed studies found the AR wayfinding systems to be highly useful and enjoyable. Preference for AR over traditional methods such as digital or paper maps was often linked to interactivity, engagement, and entertainment value—factors that designers can leverage to improve the user experience and acceptance of the technology. Incorporating diverse modalities and personalization options so that users can tailor the experience to their personal needs and preferences will likely further enhance this positive reception. We recommend that AR system designers carefully study this literature to become aware of users' preferences and potential pitfalls, and that new systems be carefully user-tested to check for emerging problems. At the same time, we note that many studies included in our review did not report sufficient technical details of their AR applications, such as the development platform or tracking techniques, that would be useful to reach comparative conclusions or inform AR designers. The absence of technical details in some studies highlights a broader issue of standardization in the research field. Although it is challenging to establish a standardized reporting format for a new technology used across diverse disciplines, researchers should carefully consider the replicability and comparability of their study protocols and at a minimum provide full details about the AR technologies used.

When it comes to the effects of AR on wayfinding performance, findings in the literature were mixed. This was particularly the case when contrasting indoor vs. outdoor contexts. In indoor environments, AR consistently outperformed conventional methods such as paper or 2D digital maps, reducing task completion times and navigational errors. It was more common in outdoor navigation for studies to find no substantial differences between AR and conventional guidance. This outcome likely indicates that wayfinders were using different cues or navigational strategies in outdoor vs. indoor contexts. The enhanced effectiveness of indoor AR may also be attributed to the controlled nature of these environments, which allows for more precise and reliable technological implementations in smaller, confined areas. Other factors, such as the intensity of the outdoor lighting affecting users' perception, or greater perceived safety concerns when navigating outdoors, may play a role. Another highly notable finding in this area is that all of the studies that found no positive performance impact of AR were conducted using handheld devices. We suggest that the requirement for constant physical engagement with the handheld platforms might be a contributing factor that detracts from the effectiveness of AR, especially in outdoor contexts; however, more research would be needed to confirm this.

Concurring with user's greater preference for visual guidance, we found that this type of data-presentation typically outperformed auditory guidance in enhancing wayfinding outcomes. Tactile guidance provided the least wayfinding performance benefits, but it was only evaluated in a single study, and thus, more research is needed to draw any conclusions about this novel modality. The inclusion of interactive maps as part of the AR experience was consistently shown to improve wayfinding performance compared to purely directional guidance. However, users relied on the directional guidance more often than maps at important decision-making points, highlighting the centrality of overlayed path visualizations. Overall, the evidence collectively indicates that the effect of AR on wayfinding performance is highly context-dependent, influenced by variables such as gender, engagement level, device used, accuracy in localization, visibility of navigational cues, type of environment, and design considerations. Unfortunately, most of the existing literature has considered only one or two of these variables at a time, making it difficult to draw broader conclusions across disparate studies. Researchers should continue to pursue comparative studies that will directly juxtapose multiple variables within the same experiment framework, for example, by using different device types and multiple feedback strategies across both indoor and outdoor routes.

Concerning the cognitive effects of using AR navigational tools, a central finding of the review is that a large body of literature employing varied measurement methods has demonstrated that AR reduced mental workload in comparison to non-AR wayfinding. This was manifested in multiple ways, including assessment surveys such as the NASA-TLX and eye-tracking measures such as fixation durations. Generally, participants using AR through head-mounted displays reported lower cognitive load than mobile devices, and both were found to be superior to paper maps or unguided navigation. Additionally, visual guidance reported a lower cognitive load than audio guidance. These findings about cognitive load strongly overlap with the wayfinding performance outcomes and with the user preferences regarding these modalities. The results are consistent with Cognitive Load Theory as applied to AR, which holds that the technology's in-context presentation of information can reduce the mental effort required to understand and assimilate navigational guidance. By off-loading the mental task of processing and visualizing navigation guidance to real-world overlays, AR presents a more streamlined and less distracting experience (Fan et al. 2020; Kim and Dey 2016).

The majority of the reviewed studies found that AR significantly aided cognitive map development compared to conventional forms of navigational guidance. This is again consistent with the split-attention effect from the Cognitive Load Theory, which holds that the reduction in effort obtained from a direct and immersive presentation of spatial information will leave more cognitive resources available for the robust formation of maps (Goff et al. 2018). Nevertheless, one study in our review (Rehman and Cao 2017) found that reduced cognitive workload from using AR did not translate into better cognitive maps, with the AR group actually scoring significant worse in terms of route memory errors, possibly due to the deficiencies of digital navigation guidance in aiding user understanding of the routes. This inconsistency may stem from the interaction between AR interfaces and natural human navigation skills. In some cases, AR provides detailed guidance without necessitating user engagement with environmental landmarks, which may result in users not fully processing contextual cues and consequently developing weaker spatial memory. In other scenarios, overlaying AR navigational guidance with environmental cues that prompt users to actively make their own navigational decisions and recognize landmarks can potentially enhance cognitive map formation. This finding appears to be idiosyncratic, but it is an important caution suggesting that more research is needed to investigate how different AR devices, information modalities, and environmental contexts may intersect to influence spatial knowledge acquisition.

Current AR solutions predominantly offer generalized wayfinding guidance without catering to individual needs such as preferences and expertise levels. In addition to decreasing overall user acceptance of the technology, this lack of adaptation could potentially lead to an overreliance on AR and a stifling of spatial learning as active users come to expect a certain level of guidance. We noted that most studies in our review focused on measuring the immediate effects of AR use, without considering its long-term cognitive effects. Given the limited research in this area, and the potentially significant implications of regular use of AR for cognitive skills development and maintenance, it is crucial that more work should be done to investigate the potential long-term cognitive effects of AR navigational aids. It could be most effective to devise scaffolding mechanisms that tailor AR guidance to an individual's cognitive processes, or that serve to reinforce skills-based navigation and learning (Moghaddam et al. 2021).

6 Limitations and suggestions for future research

Methodologically, this systematic literature review is constrained by its selection criteria; for example, it does not address AR-supported navigation while driving an automobile or navigation within fully virtual environments. The exclusion of studies not written in English may have resulted in some relevant articles being overlooked. It should also be noted that the number of included studies was somewhat thin in certain areas of our research interest. User experience issues were discussed in 49 of the included studies, but there were only 29 studies in the review that addressed wayfinding performance, and only 18 that addressed spatial cognition. We did not find any studies at all addressing AR's relation to navigational decision-making processes or specific wayfinding behaviors. Moreover, many of the studies in the review suffered from small sample sizes, often including fewer than 10 participants. This scarcity of data may limit their ability to derive statistically significant insights. It is not entirely surprising to see a dearth of research literature in these areas since AR is a relatively new technology; however, the low number of studies on some topics means that the review's conclusions should be considered provisional until further research can be conducted.

Additional considerations that may have affected the insights attained during the literature review include the low number of studies considering confounding factors such as participants' gender, age, and geographic background, and the tendency of many included studies to use oversimplified wayfinding tasks (e.g., tasks that do not require a change in floor level). Most of the experiments were quite brief (less than 20 min) and therefore may not reflect the user experience of individuals who employ AR devices for extended periods of time. The different types of buildings and unique navigational tasks used in each study can reduce the ability to compare and generalize their findings. Several studies in our review reported technical difficulties such as lagging and inaccurate localization; while these issues seem to improve over time as the technology matures, researchers should carefully pilot-test their approaches to reduce the number of such glitches. Most of the studies reported scant details about their AR system configurations and technical implementations, making it hard to draw conclusions about optimal approaches for different use cases or how these technical configurations may have affected the study outcomes.

Future research should strive to expand the scope and robustness of AR wayfinding studies, by simultaneously considering more variables in the same experiment, obtaining larger and more diverse participant samples, and using more complex and realistic wayfinding tasks. A central goal should be to delve deeper into specific AR design and configuration considerations, and to investigate the nuanced interplay between different information modalities. In the current literature review we had to rely on comparing disparate studies that used distinct wayfinding tasks and protocols to synthesize an overview perspective. Future researchers can build upon the review's conclusions by directly integrating the emerging variables of interest, for example by conducting mixed inside/outside research with both handheld and head-mounted AR displays and various information modalities. This can help to determine if the inside/outside differences noted in the literature review are replicable, and provide insights about the potential underlying mechanisms of such differences. These targeted efforts will help to build a more robust and thorough understanding of the role and potential of AR navigation technology to improve users' wayfinding experiences.

Appendix

See Table 5.

Table 5 Results of MMAT quality assessment

	References	Assessment Score (Total of 17)
1	Stigall et al. (2019)	6.7
2	Rochadiani et al. (2022)	6.1
3	Ahmad et al. (2005)	13.5
4	Kim et al. (2015)	14.0
5	Smith et al. (2017)	10.3
6	Ping et al. (2020)	16.5
7	Hou and Tang (2020)	11.9
8	Arntz et al. (2020)	15.5
9	Romli et al. (2020)	3.8
10	Drewlow et al. (2022)	4.75
11	Sheoprashad and Defreitas (2022)	6.5
12	Wakchaure et al. (2022)	5.5
13	Yunardi et al. (2022)	6
14	Sharin et al. (2023)	4.75
15	Kluge and Asche (2012)	8
16	Schougaard et al. (2012)	5.5
17	Rehrl et al. (2014)	14.25
18	Rovelo et al. (2015)	15
19	Chin and Lee (2015)	2.25
20	Amirian and Basiri (2016)	11.5
21	Brata and Liang (2020)	6.75
22	Tang and Zhou (2020)	13.75
23	Anbaroglu et al. (2020)	12.25
24	Ng and Lim (2020)	6.6
25	Lee et al. (2020)	13.75
26	Kamalam et al. (2022)	3
27	Preethaet al. (2023)	6.25
28	Gerstweiler et al. (2017)	14
29	Nizam et al. (2021)	5
30	Kasprzak et al. (2013)	15
31	Rubio-Sandoval et al. (2021)	13
32	Calle-Bustos et al. (2021)	13.75
33	Zhang and Nakajima (2020)	5
34	Joo-Nagata et al. (2017)	8.25
35	Montuwy et al. (2019)	14.75
36	Huang et al. (2012)	13.25
37	San Martin and Kildal (2021)	14.75
38	Chaturvedi et al. (2019)	12.5
39	Ajmi et al. (2019)	7.0
40	Makimura et al. (2019)	13.75
41	Rehman and Cao (2017)	15.5
42	McKendrick et al. (2016)	15.25
43	Lee (2022)	15.2
44	Debandi et al. (2018)	10.1
45	Lu et al. (2021)	12.25
46	Araujo et al. (2019)	10.9
47	Nenna et al. (2021)	16.25
48	Dunser et al. (2012)	15.5
49	Liu et al. (2021)	14
50	Kuwahara et al. (2019)	10.75
51	Torres-Sospedra et al. (2015)	2.4
52	Huang et al. (2019)	14.25
53	Munoz-Montoya et al. (2019)	8.25
54	Sekhavat and Parsons (2018)	15
55	Zhao et al. (2020)	15.5

Table 5 (continued)

	References	Assessment Score (Total of 17)
56	Truong-Allie et al. (2021)	15
57	Goldiez et al. (2007)	14.6
58	Dong et al. (2021)	15.5
59	Zhang et al. (2021)	15.5
60	Mulloni et al. (2011b)	4
61	Xie et al. (2022)	15.5
62	Mulloni et al. (2012)	11.25
63	Mulloni et al. (2011a)	15.1
64	Kerr et al. (2011)	14.5
65	Möller et al. (2014)	16.5
66	Qiu et al. (2024b)	16.5
67	Valizadeh et al. (2024)	6.5
68	Lakehal et al. (2023)	11.5
69	Xu et al. (2024)	16.5
70	Fajrianti et al. (2023)	12.1
71	Pesaladinne et al. (2023)	7.3
72	Qiu et al. (2024a)	15.5
73	Xie et al. (2023)	12.1
74	Truong-Allié et al. (2023)	16
75	Bibbò et al. (2024)	10.9
76	Romli et al. (2024)	4.8
77	Nendya et al. (2023)	7.3
78	Qi et al. (2024)	4.8
79	Bide et al. (2023)	6.1
80	Sundarramurthi et al. (2023)	4.8
81	Maran et al. (2023)	4.8
82	Harwati et al. (2024)	4.8
83	Sharma (2023)	7.3
84	Achmad et al. (2024)	6.1
85	Safranoglou et al. (2024)	7.3
86	Kumaran et al. (2023)	16
87	Park et al. (2024)	15
88	Mazurkiewicz et al. (2023)	16

Author contributions All authors participated in registering the protocol. CQ and AM were responsible for screening articles, while SK assisted in resolving any disputes. All authors contributed to writing the main manuscript and conducted a thorough review of the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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