

# Echolocation-based Smartphone Assistive Applications in Spatial Perception and Navigation for Blind and Low Vision Users: A Systematic Review

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## Abstract

*With the expected increase of blind and low vision (BLV) individuals, supporting spatial perception and navigation is critical. Echolocation is recognized as effective in conveying spatial information, and the advancement of smartphone technologies has prompted interest in its use as assistive technology. This systematic review assesses the potential of echolocation-based smartphone assistive applications (EBSAs) and formulates a set of design principles to guide future research and implementation. Of the 17 included studies, nine described echolocation-based assistive technologies (EBATs) and eight discussed smartphone assistive applications. Findings reveal that EBATs, and smartphone assistive applications facilitate information gain, ease-of-use, and independence. However, EBATs can present steep learning curves and technological limitations, whilst smartphone applications are limited by sensory inaccuracy and compatibility issues. The findings of this study highlight the need to improve user-centric design, integrate existing technologies and multimodal feedback, as well as encourage stakeholder collaboration in design, development, and testing.*

**Keywords:** echolocation assistive technology, smartphone assistive application, human echolocation technology, navigation assistive application

## 1. Introduction

Globally, there are 43 million blind individuals and 295 million people with low vision. Due to population growth, urbanization, and longer lifespans, vision loss is expected to affect 895 million people by 2050, including 61 million who will be blind (Orbis, 2021). Eye health, encompassing ocular health and functional ability, impacts an individual's social inclusion, quality of life, and overall well-being, whereas poor eye health restricts social participation, access to education, and employment opportunities (Burton et al., 2021). The WHO (2024) identifies the development of evidence-based services and assistive technologies as crucial to ensure independence and mobility of BLV individuals.

Spatial perception refers to orientation in an environment, while navigation involves determining a route to a destination (Gori et al., 2017). Common mobility aids for these are guide dogs and white canes. Some people use natural echolocation for spatial perception, though only 20-30% use it effectively due to extensive training requirements, making it effective yet mostly inaccessible (Thaler & Goodale, 2016).

Therefore, recent research explores echolocation in modern assistive technologies. Wearable devices, such as head-mounted or wrist-worn, are common. Their adoption is influenced by factors like comfort, confidence, mobility, and adaptiveness (Messaoudi et al., 2022). Additionally, integrating assistive technologies into smartphone applications is an emerging industry trend as it can add aspects often lacking in current solutions, like convenience, adaptiveness, and portability (Theodorou et al., 2022). To further explore the impact of implementing EBATs as smartphone applications, this research explores the features and usability of EBATs and smartphone assistive applications. Based on this, design principles are formulated to guide the research and implementation of EBSAs to support BLV users in spatial perception and navigation. The research question (RQ) is posed:

**RQ:** Which factors should be considered in the design, development, and testing of EBSAs?

## 2. Theoretical Background

Visual input is essential for human spatial perception, enabling the perception of distance, depth, and motion (Voss, 2016). Initially, vision loss was thought to impair spatial perception and navigation ability. However, Loomis (2002) suggests that sensory substitution allows individuals to compensate for sensory loss by using other functional senses to perceive the environment. This principle underlies mobility aids for BLV users, allowing them to perceive visual information through sound or touch (Loomis, Klatzky & Giudice, 2012).

Tactile sensory substitution devices (SSDs) are advantageous due to the ease and efficiency of converting visual information to tactile form (Csapó &

Wersényi, 2013). Users can receive a broad range of tactile sensations and understand the environment despite background noise distractions. However, tactile SSDs only convey information about immediate objects, posing challenges in complex environments (Loomis, Klatzky & Giudice, 2012).

Auditory SSDs, despite their steeper learning curve and potential background noise interference, can convey detailed spatial information (Bharadwaj, Shaw & Goldreich, 2019). Brain imaging conducted by Levy-Tzedek et al. (2012) shows that auditory feedback is often more effective than tactile for conveying spatial information in congenitally blind and sighted individuals. Auditory feedback results in a lighter cognitive load and is often preferred by users in spatial perception tasks (Real & Araujo, 2019). Auditory sensory substitution also facilitates the development of cognitive mapping, enhancing spatial memory and navigation skills (Loomis, Klatzky & Giudice, 2012).

Auditory SSDs are categorized into verbal and sonified sensory substitution (Csapó & Wersényi, 2013). Speech-based or verbal auditory feedback uses natural language to convey information, allowing it to describe details and identify objects or labels (Chundury et al., 2022). However, it is slower for the user to process and less effective for continuous information relay (Csapó & Wersényi, 2013). Sonification, which uses non-verbal feedback like environmental sounds or simulated echolocation, is sometimes preferred in spatial perception as it can convey a variety of information quickly (Csapó & Wersényi, 2013). Although learning to interpret soundscapes requires more training, sonification can communicate the presence of stationary and moving objects, as well as their size, texture, relative location, and motion, enabling independent navigation (Chundury et al., 2022; Bujacz & Strumiłło, 2016).

Echolocation, the ability to produce sounds and use their echoes to perceive the environment, has influenced the development of auditory SSDs (Kolarik et al., 2014). Early studies about human echolocation, such as McCarthy & Worchel's (1954) study highlight its functional benefits in spatial perception. They observed a blind child using mouth clicks to navigate around silent obstacles while riding a bicycle, demonstrating effective spatial awareness using echolocation. Kolarik et al. (2014) found that the frequency, volume, and direction of echoes provide information about the properties of detected objects. Similarly, Thaler (2013) emphasizes that echolocation enhances BLV individuals' ability to determine the relative distance, position, motion, size, shape, and texture of nearby objects. Studies consistently agree that echolocation increases spatial awareness and allows forming a comprehensive mental map of the environment (Kolarik

et al., 2014). This mental map is crucial for independent mobility, as it enables safe and effective navigation.

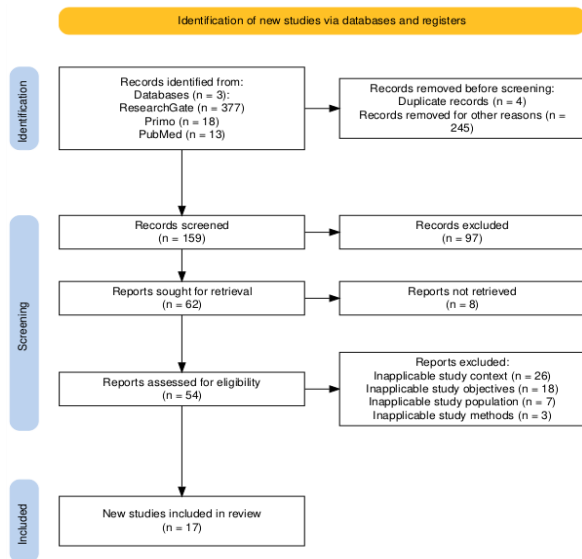
Still, the guide dog and the white cane remain the most common mobility aids for BLV users. Guide dogs are trained in complex tasks like wayfinding and object detection, but their upkeep is costly, and they require continuous care (Scalvini et al., 2023). Conversely, white canes are cost-effective but limited to detecting immediate objects and require constant user vigilance (Scalvini et al., 2023). Early electronic travel aids significantly impacted the development of technological solutions for object detection and avoidance (Kuriakose, Shrestha & Sandnes, 2020). Still, they faced poor adoption due to excessive costs, bulky designs, and limited functionality (Real & Araujo, 2019). The poor understanding of BLV users' needs further hindered success. Navigation assistive technologies have advanced in recent decades, though many face usability challenges due to complex interfaces and learning curves (Kuriakose, Shrestha & Sandnes, 2022). Multipurpose assistive technologies, such as Aira, connect BLV users with sighted individuals through smartphone applications. Nguyen et al. (2019) found that 33% of calls made to Aira over a three-month period were for navigational assistance, highlighting the demand for smartphone-usable navigation assistive technologies.

### 3. Methods

This section describes the data collection approach and the formulation of design principles in the study.

#### 3.1. Material collection

Following Webster & Watson (2002), this paper embodies the state of the field and identifies research gaps by reviewing existing literature. The study uses both qualitative and quantitative data to evaluate the user perception and usability of EBATs and their implementation as smartphone applications. The study relies on secondary sources, including journal articles and conference proceedings. Material is collected using Webster & Watson's (2002) concept-centric approach and reports the items using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (PRISMA, 2020).



**Figure 1. PRISMA flow diagram for retrieving literature (Haddaway et al., 2022)**

Literature was sourced from Primo (a meta-search engine including over 120 databases such as ACM Digital Library, IEEE Xplore Digital Library, JSTOR, and more), ResearchGate, and PubMed databases. The search was conducted on 9 April 2024, and results were filtered to include studies published after 2010 to ensure the inclusion of relevant research contributions, while still considering the fast-paced development of modern technology. Keywords included “echolocation assistive technology,” “smartphone assistive application,” “human echolocation technology,” and “navigation assistive application.” Studies were categorized into EBATs and smartphone assistive applications.

A review was conducted to bridge two existing research areas by synthesizing key findings and identifying unmet needs. Given the limited research on EBSAs, the reproducibility and process transparency of a systematic review offered an objective view of the technological landscape as it reduced bias and ensured consistent source quality. Despite limited research, it facilitated an exhaustive analysis of existing findings considering the study scope, allowing the development of guidelines for an emerging field.

Each study was screened by title and abstract, and initially included or excluded based on non-English language, non-human or non-technological applications, and lack of primary data (Figure 1). Selected studies were reviewed against final inclusion criteria (Table 1). The criteria considered the defined study scope by specifying context, user group, and study objectives. To gain a complete understanding of user experience, primary research from user studies, interviews and questionnaires are included.

**Table 1. Inclusion criteria of the literature search**

Context	Spatial perception and navigation
Population	Blind and low vision individuals
Objective	Usability or user experience of EBATs
	Usability or user experience of smartphone assistive applications
Methods	Quantitative or qualitative observations obtained from a user study
	Quantitative or qualitative user feedback gained from interviews or questionnaires

### 3.2. Development of design principles

This study formulates design principles for the development of EBSAs to assist BLV users in spatial perception and navigation. Design principles are created based on a comparative analysis of various EBATs to identify features, benefits, and challenges. A similar assessment is conducted for smartphone assistive applications, emphasizing barriers to adoption, usability, and user experience. Findings are then synthesized to identify gaps in research, highlighting areas of improvement. Finally, a set of design principles is formulated to address the improvement areas of current assistive technologies. The evolving nature of technology is considered to develop reusable guidelines to lead future research and implementation (Gregor, Kruse & Seidel, 2020).

## 4. Results

Of the 17 studies, nine studies focus on echolocation technologies, all published after 2015. Seven studies about smartphone assistive applications were published after 2020, indicating growing interest in the field. The study objectives are to support users in spatial perception and navigation, including obstacle detection and avoidance (n=11), route planning and navigation (n=4), object recognition and identification (n=5), and other contextual information (n=3), with some studies addressing several. Obstacle detection and avoidance was the focus of all EBATs (n=9). Cultural and geographical contexts influenced the perception of disability and the use of assistive technologies. Studies include research from the USA (n=3), Pakistan (n=3), Canada (n=2), Taiwan (n=2), Greece (n=1), Mexico (n=1), Brazil (n=1), the UK (n=1), Romania (n=1), Japan (n=1), and China (n=1).

Technical metrics and user feedback are used to assess the proposed systems. Several systems use research team observations (n=13), while others utilize user interviews and post-trial questionnaires (n=12). Some studies employ both. Quantitative metrics include measurement accuracy (n=5), task completion time (n=5), system reliability (n=4), and user performance

(n=4). Resource (e.g., CPU and battery) usage are also measured (n=2). Qualitative measures assess the user's perceived achievement of the goal (n=8), ease-of-use and cognitive load (n=8), and emotional response (n=5). Still, studies note the impact of individual circumstances like level of vision and characteristics of vision loss, on the metrics which are mostly unaddressed by the results.

#### 4.1. EBATs

Most EBATs performed spatial mapping using ultrasonic sensors (n=5), sonar sensors (n=1), infrared cameras (n=1), and LiDAR sensors (n=1). One study used a VR headset with a 3-D motion-tracking device (Massiceti, Hicks, and van Rheede, 2017). Use cases included obstacle detection and avoidance (n=9), object recognition (n=3), navigation (n=1), and object identification (n=1). Some devices were specified for indoor (n=1), outdoor (n=1), or both environments (n=1). Seven EBATs were wearable, while two were handheld. Two of the wearable devices were head-mounted, while others were worn on the shoe (n=1), wrist (n=1), and chest (n=1). One EBAT was worn on the head, wrists, and ankles. Each device used auditory feedback for spatial information, with eight using sonification. Ton et al. (2018) represented nearby objects using high-frequency sound and distant objects with lower-frequency sounds. Ye et al. (2019) used volume, frequency, and sound phase differences to represent object details. Three studies supplemented sonification with tactile vibrations for additional information gain. Watanabe, Sumiya & Terada (2022) used machine learning for object recognition, resulting in supplementary tactile notifications. Two studies used verbal feedback to describe objects with sonification.

**4.1.1. Benefits.** Seven studies highlighted information gain as a benefit. Watanabe, Sumiya & Terada (2022) reported a notable decrease in object detection time from 71.5 seconds to 45.9 seconds. Users in other studies made accurate lateral and distance judgments and could perceive additional information, such as object shapes and textures with minimal training. Moreover, EBATs allowed users to detect objects above ground level. Natural echolocation abilities were also enhanced by improving the user's ability to detect and identify objects, increasing the efficiency and quantity of information gain (Sohl-Dickstein et al., 2015; Silva et al., 2022). Furthermore, the option to incorporate multimodal feedback allowed users to pinpoint objects and make faster spatial judgements (Watanabe, Sumiya & Terada, 2022).

Six studies noted high accuracy and precision of distance judgements, with many achieving 92.5-100% accuracy, and three studies reaching 100% precision in

obstacle detection tasks (e.g., Ahmed, et al., 2022; Sohl-Dickstein, et al., 2015). The ability to detect objects at distances up to 4.1 meters was also viewed as an advantage (Munteanu & Ionel, 2016; Ahmed, et al., 2022; Ton et al., 2018).

Six studies cited ease-of-use as a benefit, with portability and low physical demand being contributing factors. EBATs reduced physical and mental workload, and decreases were noted in mental demand, effort, and frustration (Syed & Mehmood, 2021; Watanabe, Sumiya & Terada, 2022). The ability of EBATs to integrate with human spatial hearing enabled forming intuitive spatial judgments about the environment (Sohl-Dickstein et al., 2015).

Despite learnability challenges, four studies reported rapid user performance improvement with minimal training. Users showed improvements in navigation time and detection accuracy as some users learned to navigate effectively within five days (e.g., Massiceti, Hicks & van Rheede, 2017; Ye et al., 2019). Customizability of feedback, specifically incorporating multimodal feedback, further improved learning (Munteanu & Ionel, 2016; Ton et al., 2018).

EBATs positively impacted user confidence, independence, and sense of accomplishment in four studies. Two studies attribute user confidence and the high sense of accomplishment to the participants' ability to use their own senses to interpret auditory cues (Sohl-Dickstein, et al., 2015; Watanabe, Sumiya and Terada, 2022). Surveys showed further increase in confidence with the use of multimodal feedback, such as tactile vibrations (Silva et al., 2022; Sohl-Dickstein et al., 2015; Watanabe, Sumiya & Terada, 2022).

Three studies mentioned the integration of echolocation technology into smartphones as a benefit, with two devices already incorporating some smartphone connectivity. Two studies also highlighted the relative affordability of EBATs compared to other assistive technologies (Syed & Mehmood, 2021; Ahmed, et al., 2022).

**4.1.2. Challenges.** Overall, EBATs were limited by a steep learning curve (n=7). The unintuitive nature of sonification led to difficulties interpreting sonified feedback in five studies. As a result, Munteanu & Ionel (2016) included an introductory trial to familiarize users with different sound frequencies, though this initially limited user independence. Participants in Massiceti, Hicks & van Rheede (2017) reported hesitancy and a lack of confidence with limited training, initially increasing cognitive load.

Overall, four studies highlighted difficulties in interpreting the received auditory feedback. One study found distinguishing sound frequencies challenging, while two studies noted variability in the users' depth

and elevation judgments (Sohl-Dickstein et al., 2015; Watanabe, Sumiya & Terada, 2022; Ton et al., 2018). Massiceti, Hicks & van Rheede (2017) reported performance variability depending on the chosen echolocation approach and noted that poor spatial memory could lead to disorientation.

Technological limitations also challenged usability (n=4). Three studies reported erroneous object detection results and limited processor performance with irregular surfaces or angled objects, causing confusion and safety concerns (e.g., Munteanu & Ionel, 2016; Syed & Mehmood, 2021). Ye et al. (2019) also noted processor performance issues due to the need to make devices portable.

Limited realistic user testing was mentioned by three studies. Six studies conducted trials with blindfolded sighted participants, whereas one study included BLV echolocation experts. Massiceti, Hicks & van Rheede (2017) noted that congenitally blind users may have altered representations of locomotor space, resulting in differing needs compared to sighted peers. Controlled environments were also a limitation as they failed to account for background noise and real-world conditions (Sohl-Dickstein et al., 2015; Watanabe, Sumiya & Terada, 2022).

## 4.2. Smartphone assistive applications

The smartphone assistive applications used built-in technology like GPS, gyro-based sensors, and other sensory capabilities. Primary use cases were navigational assistance and pedestrian mobility tracking (n=3), obstacle avoidance and recognition (n=2), and other contextual information (n=3). Two studies noted that the applications are designed to complement, not replace, conventional mobility aids as discussed in Martiniello et al. (2023). Auditory feedback, particularly sonification, was a common feedback modality (n=5). Three studies used speech-based instructions. The ISAS application used verbal descriptions for nearby locations, while the teleguidance-based assistant and BlindRouteVision provided continuous speech-based guidance (Blum, Bouchard & Cooperstock, 2012; Chaudary et al., 2021; Theodorou et al., 2022). Some applications used spatialized audio to indicate the direction of locations and obstacles (n=2), providing immersive auditory cues (Blum, Bouchard & Cooperstock, 2012; See, Sasing & Advincula, 2022). Two studies used tactile feedback to complement auditory cues as Velazquez Guerrero et al. (2021) used in-shoe vibrations to provide directional instructions. Several solutions integrated external services into the application (n=5). Blum, Bouchard & Cooperstock (2012) used commercial location databases for spatial information, while Chaudary et al.

(2021) and Velazquez Guerrero et al. (2021) incorporated a smart cane and an in-shoe device for additional feedback. Other studies used urban infrastructure to enhance road crossing information and GPS accuracy (Huang, Wu & Liu, 2022; Theodorou et al., 2022).

**4.2.1. Benefits.** The perceived usefulness for spatial perception and navigation was noted in six studies. Martiniello et al. (2023) found that 96% of respondents valued smartphone applications, which were especially popular for independent travel among younger users. Other studies noted high travel efficiency and positive feedback on the usefulness, ease, and efficiency of the applications (Velazquez et al., 2021; Theodorou et al., 2022). Chaudary et al. (2021) emphasized connecting BLV users with sighted guides for navigation in unfamiliar environments. Hamilton-Fletcher et al. (2024) cited estimation accuracy, while still maintaining battery efficiency as a key contributor to the perceived helpfulness.

Six studies reported simplicity, ease-of-use, and learnability as a benefit. Chaudary et al. (2021) noted high user satisfaction, with a 4.4 rating on a scale from -5 to 5. Theodorou et al. (2022) and Velazquez Guerrero et al. (2021) found that the applications did not add cognitive load and were practical and intuitive. Huang, Wu & Liu (2022) and See, Sasing & Advincula (2022) highlighted that the applications were already integrated into daily activities, making them easy to learn and comfortable to use.

Four studies cited information gain as a particular advantage. Chaudary et al. (2021) and See, Sasing & Advincula (2022) noted far detection distance as an advantage, with most devices detecting objects up to four meters away. The use of advanced smartphone technology in See, Sasing & Advincula's (2022) research, allowed users to sense obstacles at full-body length, which is often challenging using conventional mobility aids. Theodorou et al. (2022) found that quick application response times increased the quantity of perceivable spatial information. Blum, Bouchard & Cooperstock (2012) and Theodorou et al. (2022) emphasized the ability to iterate the application based on user feedback, enabling continuous improvement.

Four studies mentioned increased feelings of personal security and independence as a benefit. See, Sasing & Advincula (2022) and Theodorou et al. (2022) reported that the applications were perceived as safe and reliable. Chaudary et al. (2021) noted that users felt more independent and secure, reducing the need to ask for outside help.

Three studies highlighted affordability and portability. Velazquez Guerrero et al. (2021) noted that most people, including BLV individuals, already own

smartphones, making implementation feasible and favorable for the user. See, Sasing & Advincula (2022) also emphasized the lack of additional hardware costs. The applications were lightweight and easy to carry, not impacting walking speed.

Three studies mentioned the integration capabilities of smartphone platforms. Huang, Wu & Liu (2022) found that connectivity with external communication systems increased the interactivity of essential urban infrastructure, further narrowing the gap between BLV individuals and sighted peers. Theodorou et al. (2022) also noted integrating built-in accessibility features like screen readers as a benefit to improving users' ability to interact with applications independently and provide accessibility for users with varying levels of vision.

**4.2.2. Challenges.** Four studies reported limitations of built-in sensors. Blum, Bouchard & Cooperstock (2012) showed inconsistent error estimates, leading to incorrect location rendering. Hamilton-Fletcher et al. (2024) found differences in error measurements based on sensory technology and data processing approach, impacting distance estimates. See, Sasing & Advincula (2022) noted that while the application detected objects up to eight meters away, reliability decreased beyond two meters. Measurement accuracy was also influenced by walking speed. Inaccuracies in image periphery, processing delays, and high battery consumption were also observed (Hamilton-Fletcher et al., 2024; Martiniello et al., 2023).

Four studies mentioned issues with integrating built-in smartphone accessibility features. Theodorou et al. (2022) noted a lack of support for virtual assistants, while Blum, Bouchard & Cooperstock (2012) found that incompatibilities with iPhone VoiceOver technology required manual intervention from the research team. Chaudary et al. (2021) reported that the application could not run simultaneously with other applications, causing user frustration. See, Sasing & Advincula (2022) also highlighted compatibility differences between different smartphone platforms.

Three studies observed negative emotions due to complex user interfaces and overwhelming information, causing exhaustion and feelings of passiveness (Blum, Bouchard & Cooperstock, 2012; Huang, Wu & Liu, 2022; Chaudary et al., 2021). Additionally, two studies cited loud ambient sounds as a distraction. Martiniello, et al. (2023) found that 54.55% of respondents found this significantly challenges the interpretation of auditory cues. Huang, Wu & Liu (2022) reported that low volume discouraged users, while Chaudary et al. (2021) found poor internet connectivity limited navigation.

Two studies discussed the limited ability of applications to meet the users' needs. Theodorou et al.

(2022) and Martiniello et al. (2023) highlighted the lack of customizability and consideration of different user demographics, concluding that 50% of respondents felt current technologies did not fully meet their navigation needs. Moreover, Martiniello et al. (2023) found that many BLV individuals do not use smartphone assistive applications due to a lack of knowledge of their benefits and use cases.

### 4.3. Synthesis of findings

Martiniello et al. (2023) identified ease-of-use, accessibility, and price as primary factors influencing the adoption of navigation assistive technologies. Common use cases are obstacle detection, object recognition, route planning, and other contextual information. Both EBATs and smartphone applications primarily provide spatial information using auditory feedback. EBATs use sonification to emulate natural echolocation, while smartphone applications incorporate sonification, spatialized audio, speech-based feedback, and tactile vibrations. The availability of multimodal feedback was highlighted as a benefit as it provided users with additional spatial information. It also aided information gain in distracting environments.

Smartphone applications were perceived as helpful for the intended purpose, contributing to the user's willingness for continuous use as smartphones are used daily, adopting another application was viewed as easy and comfortable. Therefore, learnability and ease-of-use were primary reasons for high user satisfaction. In contrast, learnability was a challenge for EBATs as sonification cues required time and effort to learn to interpret, initially limiting user independence. However, observations noted rapid improvements in distinguishing auditory cues and using them to make both general and specific spatial judgements. Despite learnability challenges, EBATs showed potential for long-term ease-of-use as they eased the cognitive workload associated with spatial perception tasks. Similar benefits were noted in smartphone assistive applications. Efficient spatial information gain can therefore be viewed as a major benefit of both EBATs and smartphone applications.

As affordability is a key factor influencing adoption, the integration of existing smartphone technology was beneficial. Although most EBATs are considered affordable compared to other SSDs, they still require purchasing external hardware. Conversely, the built-in sensory technology and advanced capabilities of smartphones allowed the user to perceive the environment without requiring additional hardware. This increases the perceived affordability of assistive applications as smartphones are viewed as a commonplace item. Although using built-in

technologies is a recognized benefit, integrating external infrastructure provided the user with relevant and timely information, improving societal inclusion. Despite compatibility challenges, the ability to interact with the application using built-in accessibility software further eased interactivity and ease-of-use for BLV users with varying needs. This indicates that connectivity with external infrastructure and compatibility with accessibility features should be prioritized in developing new assistive technology.

Although the studied EBATs and smartphone applications were perceived as helpful in meeting a need, technological limitations affected the adoption of both technologies. The high accuracy of distance estimates was an advantage of EBATs. However, some studies reported that the need to make EBATs portable and lightweight limited their processing capabilities. Smartphone applications were commonly limited by inconsistent error measurements, which impacted the correctness of distance and positional estimates. These considerations emphasize a need to optimize current sensory technology and pay attention to selecting appropriate technologies for each use case.

Both smartphone assistive applications and EBATs gave the user a sense of independence, confidence, and personal security. Study participants found that in addition to supporting information gain, EBATs also increased the users' sense of accomplishment and confidence as they relied on their own senses to navigate. Additionally, the observations were made from short trials with minimal training, which suggests that the user's independence and confidence may further improve in the long-term. Simultaneously, some smartphone applications which primarily relied on verbal feedback reported feelings of passiveness and exhaustion among users. The findings emphasize a need to support the users' existing senses and skills in spatial perception as opposed to replacing them.

Finally, studies highlight the need for change as several EBATs were validated using sighted participants or BLV echolocation experts, causing gaps in the ability to address the needs of the majority target user group. Similarly, 50% of questionnaire respondents still reported needs which are not addressed in current applications, highlighting the need for improvements in development and testing.

## 5. Discussion

The explored benefits and challenges of EBATs and smartphone applications make a strong case for furthering the development of EBSAs as it takes advantage of both the spatial information capabilities of EBATs and the accessibility and convenience of smartphone applications. Limiting factors of secondary

research, such as the introduction of unintended bias are considered by including literature from multiple countries with various evaluation methods within the scope of the inclusion criteria. Therefore, this research addresses existing limitations of assistive technologies and provides a comprehensive and user-friendly alternative to current solutions. Still, the synthesis of findings indicates a need for improvement and further research is needed to consider the user's individual needs due to, for instance, differing levels of vision, additional disabilities, and the characteristics of the user's vision loss. Based on the identified improvement areas, a set of design principles (DPs) can be formulated to guide future research and implementation of EBSAs. This section identifies guiding statements for the improvement of such assistive systems to support BLV users in spatial perception and navigation. The context of the DPs is not noted separately as it is the same for each: spatial perception and navigation in familiar and unfamiliar environments. This discussion is an assessment of existing literature and does not test the developed DPs first-hand, which should be considered in future research.

**Table 2. Principle of familiarity.**

<b>DP1:</b>	<b>Principle of familiarity</b>
Aim	<i>To increase the learnability and user-friendliness of EBSAs to BLV users.</i>
Mechanism	<i>by using universally recognized voice commands and interactions used by accessibility features.</i>
Rationale	<i>because it increases familiarity, and thus allows intuitive interaction with the application.</i>

Supporting the findings of Levy-Tzedek et al. (2012) and Bharadwaj, Shaw & Goldreich (2019), standalone EBATs provide nuanced spatial information about the environment. However, the findings indicate a steep learning curve as sonified auditory cues are initially unintuitive to the user. To improve the learnability and user-friendliness of EBSAs to BLV users, researchers and software developers should leverage the familiarity of smartphone applications by incorporating universally recognized voice commands and interactions used by smartphone accessibility features (DP1). Following the conventions of accessible smartphone application design increases familiarity which allows intuitive interaction with the application, thus reducing the challenge of learnability.

**Table 3. Principle of multimodal feedback**

<b>DP2:</b>	<b>Principle of multimodal feedback</b>
Aim	<i>To support BLV users in spatial perception and navigation in versatile environments.</i>
Mechanism	<i>by providing the possibility to incorporate more than one mode of feedback.</i>
Rationale	<i>because it allows the user to customize the application to their individual needs.</i>

To support BLV users in spatial perception and navigation, developers should incorporate multimodal feedback into the application alongside sonification by providing options to integrate verbal or tactile feedback (DP2). The availability of different feedback modalities allows the user to customize the application to accommodate their needs. Providing feedback through different sensory channels further improves confidence and security. It also ensures sufficient information gain, particularly in busy environments, as supported by Csapó & Wersényi (2013).

**Table 4. Principle of technology selection.**  
**DP3: Principle of technology selection**

Aim	<i>To support the user's independence and confidence of mobility,</i>
Mechanism	<i>by identifying appropriate technologies for the specific use case,</i>
Rationale	<i>because it impacts perceived trustworthiness, thus affecting confidence and independence.</i>

Although both EBATs and smartphones contribute to the user's sense of independence and confidence, occasional erroneous estimations caused by technological limitations can cause confusion and hesitancy among users. To promote the BLV user's independence and confidence during navigation, researchers and people involved in implementation should identify appropriate technologies for the use case by assessing the properties and limitations of available sensory and processing technologies (DP3). Different use cases may differ in requirements for processing speed, distance estimation, accuracy, and resource usage. Ensuring the use of appropriate technology ultimately affects the user's perception of the reliability and trustworthiness of the application.

**Table 5. Principle of sensory support.**  
**DP4: Principle of sensory support**

Aim	<i>To support the user's independence of mobility,</i>
Mechanism	<i>by developing a solution that supports the use of the BLV user's existing senses,</i>
Rationale	<i>because supporting the user's existing sensory perception increases the sense of accomplishment, thus improving motivation and independence.</i>

In addition, to supporting independence in spatial perception and navigation, the spatial feedback provided by the application should support the user's own sensory perception by providing continuous sonified feedback (DP4). Findings show that the user's ability to make independent spatial judgements leads to an increased sense of accomplishment. On the other hand, using speech-based instructions contributes to feelings of passiveness and frustration. Therefore,

enabling the user to form independent judgements using their own senses causes feelings of accomplishment, increasing confidence and independence.

**Table 6. Principle of affordability.**

<b>DP5:</b>	<b>Principle of affordability</b>
Aim	<i>To improve the adoption of new EBSAs by BLV users through increasing affordability,</i>
Mechanism	<i>by maximizing the use of existing capabilities and reducing the need for additional hardware,</i>
Rationale	<i>Because affordability is a key contributor to the user's choice to adopt new technology.</i>

Affordability also influences the user's willingness to adopt new technology into use. Although some standalone EBATs are affordable compared to other assistive technologies, smartphone applications are perceived as a low-cost alternative as many BLV individuals already own them. Using the existing features and capabilities of modern smartphones can further increase affordability. Therefore, to further reduce barriers to access and allow BLV users to easily adopt new applications into daily use, software developers should utilize existing smartphone capabilities by reducing the need for additionally purchased hardware (DP5).

**Table 7. Principle of technological integration.**  
**DP6: Principle of technological integration**

Aim	<i>To enable better information access and improved societal inclusion of BLV users,</i>
Mechanism	<i>by providing ways to integrate the application to existing external infrastructure,</i>
Rationale	<i>because it increases the availability of spatial information and information about vital infrastructure.</i>

To contrast, the ability of smartphones to integrate external infrastructure is beneficial to improving the societal inclusion of BLV individuals. To improve BLV users' opportunities for information access and societal inclusion, people involved in implementing EBSAs should consider the integration of external infrastructure by utilizing existing services to improve the user's contextual awareness (DP6). This way, the user can gain information about essential urban infrastructure, such as street crossings and locations independently without having to rely on outside assistance.

**Table 8. Principle of collaboration.**  
**DP7: Principle of collaboration**

Aim	<i>To ensure that the application meets the needs of BLV users,</i>
Mechanism	<i>by increasing stakeholder collaboration and involving BLV individuals in the design, development, and testing of new EBSAs,</i>
Rationale	<i>because it allows researchers and developers to identify the needs of the target user group.</i>

Finally, much of the user testing for is conducted using sighted participants or BLV echolocation experts. Findings also identify a gap between the needs of BLV users and current navigation assistive technologies. This demonstrates the need to improve the collaboration between researchers, developers, and BLV individuals. Therefore, to develop assistive applications that meet the needs of BLV users in spatial perception and navigation, more emphasis should be placed on stakeholder collaboration by involving both researchers and developers in the process as well as highlighting the role of BLV individuals with various backgrounds and levels of vision in the application design, development, and user testing (DP7). This way, development can focus on improving the application based on target user feedback, thus addressing the needs of BLV users.

## 6. Conclusion

The need to develop evidence-based assistive technologies to support independent mobility is a growing area of research. Technological development and the popularization of smartphones have allowed the implementation of complex technologies, such as echolocation, as accessible and user-friendly applications. This paper presents a systematic review of the use of EBATs and smartphone assistive applications to support BLV users in spatial perception and navigation. Key findings are synthesized, based on which a set of design principles are formulated to guide the research and implementation of EBSAs.

Findings show that EBATs provide detailed spatial information, accuracy, and ease-of-use, while smartphone applications offer ease-of-use, learnability, and personal security. However, EBATs face challenges such as steep learning curves and technological limitations, and smartphone applications struggle with contextual distractions and the compatibility of accessibility features. The review supports the development of EBSAs to aid BLV users in spatial perception and navigation.

This study contributes to existing research by demonstrating the demand to integrate EBATs and smartphone assistive applications by synthesizing the findings of the key features, benefits, and challenges of both technologies. Additionally, the study formulates a set of design principles, which offers actionable guidelines for design, development, and testing, allowing future implementations to address gaps in usability, technological integration, learnability, and user experience.

## 7. References

- Bharadwaj, A., Shaw, S.B. & Goldreich, D. (2019). Comparing Tactile to Auditory Guidance for Blind Individuals. *Frontiers in Human Neuroscience*, 13.
- Blum, J.R., Bouchard, M. & Cooperstock, J.R. (2012). Spatialized Audio Environmental Awareness for Blind Users with a Smartphone. *Mobile Networks and Applications*, 18(3), 295–309.
- Bujacz, M. & Strumillo, P. (2016). Sonification: Review of Auditory Display Solutions in Electronic Travel Aids for the Blind. *Archives of Acoustics*, 41(3), 401–414.
- Burton, M.J., Ramke, J., Marques, A.P., Bourne, R.R.A., Congdon, N., Jones, I., Tong, B.A.M.A., Arunga, S., Bachani, D., Bascaran, C., Bastawrous, A., Blanchet, K., Braithwaite, T., Buchan, J.C., Cairns, J., Cama, A., Chagunda, M., Chuluunkhuu, C., Cooper, A. & Crofts-Lawrence, J. (2021). The Lancet Global Health Commission on Global Eye Health: vision beyond 2020. *The Lancet Global Health*, 9(4), e489–e551.
- Chaudary, B., Pohjolainen, S., Aziz, S., Arhipainen, L. & Pulli, P. (2021). Teleguidance-based Remote Navigation Assistance for Visually Impaired and Blind People—usability and User Experience. *Virtual Reality for Therapy, Psychological Interventions, and Physical and Cognitive Rehabilitation*, 27, 141-158.
- Chundury, P., Patnaik, B., Reyazuddin, Y., Tang, C., Lazar, J. & Elmqvist, N. (2022). Towards Understanding Sensory Substitution for Accessible Visualization: An Interview Study. *IEEE Transactions on Visualization and Computer Graphics*, 28(1), 1084–1094.
- Csapó, A. & Wersényi, G. (2013). Overview of Auditory Representations in human-machine Interfaces. *ACM Computing Surveys*, 46(2), 1–23.
- Gregor, S., Kruse, L.C. & Seidel, S. (2020). Research Perspectives: The Anatomy of a Design Principle. *Journal of the Association for Information Systems*, 21(6).
- Gori, M., Cappagli, G., Baud-Bovy, G. & Finocchietti, S. (2017). Shape Perception and Navigation in Blind Adults. *Frontiers in Psychology*, 8.
- Haddaway, N. R., Page, M. J., Pritchard, C. C. & McGuinness, L. A. (2022). PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis Campbell Systematic Reviews, 18, e1230.
- Hamilton-Fletcher, G., Liu, M., Sheng, D., Feng, C., Hudson, T.E., Rizzo, J.-R. & Chan, K.C. (2024). Accuracy and Usability of Smartphone-based Distance Estimation Approaches for Visual Assistive Technology Development. *IEEE Open Journal of Engineering in Medicine and Biology*, 5, 54–58.
- Huang, C.-Y., Wu, C.-K. & Liu, P.-Y. (2022). Assistive Technology in Smart cities: a Case of Street Crossing for the visually impaired. *Technology in Society*, 68, 101805.
- Kolarik, A.J., Cirstea, S., Pardhan, S. & Moore, B.C.J. (2014). A Summary of Research Investigating Echolocation Abilities of Blind and Sighted Humans. *Hearing Research*, 310, 60–68.
- Kuriakose, B., Shrestha, R. & Sandnes, F.E. (2020). Tools and Technologies for Blind and Visually Impaired

- Navigation Support: A Review. *IETE Technical Review*, 39(1), 1–16.
- Levy-Tzedek, S., Hanassy, S., Abboud, S., Maidenbaum, S. & Amedi, A. (2012). Fast, Accurate Reaching Movements with a visual-to-auditory Sensory Substitution Device. *Restorative Neurology and Neuroscience*, 30(4), 313–323.
- Loomis, J.M. (2002). *Sensory Replacement and Sensory Substitution: Overview and Prospects for the Future*. Reporterre, Arlington, Virginia, USA: Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Science, 213–224.
- Loomis, J. M., Klatzky, R. L., & Giudice, N. A. (2012). Sensory Substitution of vision: Importance of Perceptual and Cognitive Processing. In R. Manduchi & S. Kurniawan (Eds.), *Assistive Technology for Blindness and Low Vision*. CRC Press.
- Martiniello, N., Bleau, M., Gingras-Royer, N., Tardif-Bernier, C. & Joseph Paul Nemargut (2023). Exploring the Role of Artificial Intelligence and Inclusive Technologies during navigation-based Tasks for Individuals Who Are Blind or Who Have Low vision: Future Directions and priorities. *Research Square*.
- Massiceti, D., Hicks, S.L. & van Rheede, J.J. (2018). Stereoscopic vision: Exploring visual-to-auditory Sensory Substitution Mappings in an Immersive Virtual Reality Navigation Paradigm. *PLOS ONE*, 13(7), e0199389.
- McCarthy, B. & Worchel, P. (1954). Rate of Motion and Object Perception in the Blind. *Journal of Visual Impairment & Blindness*, [online] 48(9), pp.316–322.
- Messaoudi, M.D., Menelas, B.-A.J. & Mcheick, H. (2022). Review of Navigation Assistive Tools and Technologies for the Visually Impaired. *Sensors*, 22(20), 7888.
- Munteanu, D., & Ionel, R. (2016). Voice-controlled Smart Assistive Device for Visually Impaired Individuals. *International Symposium on Electronics and Telecommunications*.
- Nguyen, B.J., Chen, W.S., Chen, A.J., Utt, A., Hill, E., Apgar, R. & Chao, D.L. (2019). Large-scale assessment of needs in low vision individuals using the Aira assistive technology. *Clinical Ophthalmology*, 2019(13), 1853–1868.
- Orbis. (2021). *Global Blindness Was Slowing Prior to Pandemic Study Reveals*. <https://www.orbis.org/en/news/2021/new-global-blindness-data>
- PRISMA (2020). *PRISMA 2020 Statement*. PRISMA. <https://www.prisma-statement.org/prisma-2020-statement>
- Real, S. & Araujo, A. (2019). Navigation Systems for the Blind and Visually Impaired: Past Work, Challenges, and Open Problems. *Sensors*, 19(15), 3404.
- Scalvini, F., Bordeau, C., Ambard, M., Migniot, C. & Dubois, J. (2023). Outdoor Navigation Assistive System Based on Robust and Real-Time Visual–Auditory Substitution Approach. *Sensors*, 24(1), 166–166.
- See, A.R., Sasing, B.G. & Advincula, W.D. (2022). A Smartphone-Based Mobility Assistant Using Depth Imaging for Visually Impaired and Blind. *Applied Sciences*, 12(6), 2802.
- Silva, M.B.C., Bispo, B.C., Silva, C.M., Cunha, N.A., Santos, E.A.B. & Rodrigues, M.A.B. (2022). Assisted Navigation System for the Visually Impaired. In: *XXVII Brazilian Congress on Biomedical Engineering*. Cham: Springer International Publishing, 1439–1444.
- Sohl-Dickstein, J., Teng, S., Gaub, B.M., Rodgers, C.C., Li, C., DeWeese, M.R. & Harper, N.S. (2015). A device for human ultrasonic echolocation. *IEEE transactions on bio-medical engineering*, 62(6), 1526.
- Syed, Sidra Abid & Mehmood, Nimra (2019). Blind Echolocation Device with Smart Object Detection. *Quest Research Journal*, 17(2), 66–70.
- Ahmed, S.S., Khan, T., Ali, H. & Dr. Fahad Shamim (2022). Smart and Cost-Effective Device for Visually Impaired People. *International Journal of Preventive Medicine and Health (IJPMH)*, 3(1), 1–5.
- Thaler, L. (2013). Echolocation May Have Real-life Advantages for Blind people: An Analysis of Survey Data. *Frontiers in Physiology*, 4.
- Thaler, L. & Goodale, M.A. (2016). Echolocation in Humans: an Overview. *Wiley Interdisciplinary Reviews: Cognitive Science*, [online] 7(6), 382–393.
- Theodorou, P., Tsiglikos, K., Meliones, A. & Filios, C. (2022). An Extended Usability and UX Evaluation of a Mobile Application for the Navigation of Individuals with Blindness and Visual Impairments Outdoors—An Evaluation Framework Based on Training. *Sensors*, 22(12), 4538.
- Ton, C., Omar, A., Szedenko, V., Tran, V.H., Aftab, A., Perla, F., Bernstein, M.J. & Yang, Y. (2018). LIDAR Assist Spatial Sensing for the Visually Impaired and Performance Analysis. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 26(9), 1727–1734.
- Velazquez Guerrero, R., Pissaloux, E., Del Valle Soto, C., Carrasco Zambrano, M.A., Mendoza Andrade, A. & Varona Salazar, J. (2021). Mobility of Blind People Using the Smartphone's GPS and a Wearable Tactile Display. *DYNA*, 96(1), 98–104.
- Voss, P. (2016). Auditory Spatial Perception without Vision. *Frontiers in Psychology*, 7.
- Watanabe, H., Miwa Sumiya & Terada, T. (2022). Human-Machine Cooperative Echolocation Using Ultrasound. *IEEE access*, 10, 125264–125278.
- Webster, J. & Watson, R.T. (2002). Analyzing the Past to Prepare for the Future: Writing a Literature Review. *MIS Quarterly*, 26(2), xii–xxiii.
- WHO. (2024). *Eye care, Vision Impairment and Blindness*. WHO. [https://www.who.int/health-topics/blindness-and-vision-loss#tab=tab\\_3](https://www.who.int/health-topics/blindness-and-vision-loss#tab=tab_3)
- Ye, Y., Wang, K., Hu, W., Li, H., Yang, K., Sun, L. & Chen, Z. (2019). A Wearable Vision-To-Audio Sensory Substitution Device for Blind Assistance and the Correlated Neural Substrates. *Journal of Physics: Conference Series*, 1229(1), 12026–12026