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REVIEW PAPER

An insight into smartphone-based assistive solutions for visually impaired and blind people: issues, challenges and opportunities

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Abstract

Blind people are confronting a number of challenges in performing activities of daily life such as reading labels on a product, identification of currency notes, exploring unknown spaces, identifying the appearance of an object of interest, interacting with digital artifacts, operating a smartphone's user interface and selecting non-visual items on a screen. The emergence of smartphone-based assistive technologies promotes independence, ease of use and usability resulting in improved quality of life yet poses several challenging opportunities. We have reviewed research avenues in smartphone-based assistive technologies for blind people, highlighted the need for technological advancements, accessibility-inclusive interface paradigm, and collaboration between medical specialists, computer professionals, usability experts and domain users to realize the potential of ICT-based interventions for blind people. This paper analyzes a comprehensive review of the issues and challenges for visually impaired and blind people with the aim to highlight the benefits and limitations of the existing techniques and technologies. Future research ventures are also highlighted as a contribution to the field.

Keywords Assistive technologies · User interfaces · Blind-friendly UIs · Etas · Blind people · HCI

1 Introduction

Blind and visually impaired people are an important aspect of our society; a massive increase in eye-related diseases and reduction in the human vision of visually impaired people are becoming a caring dimension for the society, health institutions and government agencies to counter post-impairment challenges [1]. The loss of vision leads to compromise the ability of blind people to perform several activities of daily living (ADL) [2]. Information and Communication Technologies (ICTs) are accumulating capabilities for rapid and inexpensive solutions for blind and visually impaired people.

Worldwide [3], 285 million people are visually impaired, of which 39 million are blind, and 246 million have low vision. About 90% of the blind population is living in developing countries, out of which 82% are aged over 50. The expected population of blind people would be 75 million by 2020 [3]. This increase in the population of blind people will affect the quality of life and cause social imbalance in the future, if not addressed adequately. These issues have driven the researchers toward exploring new avenues of research across several disciplines such as assistive technologies, cognitive psychology, computer vision, sensory processing, rehabilitation and accessibility-inclusive human–computer interaction (HCI).

Assistive technology facilitates blind people to access information, promote safety, support their mobility and an improved quality of life, having a direct impact on social inclusion [4]. Research pertains to assistive technologies that are mainly focused on mobility, object identification, navigation and access to information on printed artifacts and social interaction [5]. However, the recent advances in rehabilitation engineering, cognitive psychology, computer vision, wearable technologies, multi-sensory adaptations, retinal implants, tactical displays, smart canes and smartphone-based apps open new vistas of opportunities for improving the quality of life for blind people.

Information and Communication Technologies (ICTs) are accumulating capabilities for rapid and inexpensive solutions for blind and visually impaired people. A large number of visually impaired and blind people are using state-of-the-art

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ICT-based assistive technologies in performing their daily life activities [6–8]. The vision alternatives such as speech systems [9], auditory [10], multimodal interactions [11], haptic feedback [12], vibro-tactical [13] and gesture recognition systems [14] are compensating these people in operating the touchscreen interfaces, i.e., smartphone, tablets and smartwatches.

Smartphone-based assistive technologies for blind people are an emerging trend promoting ease of use, productivity and enhanced interactions [15–17]. Blind people perform common activities either through direct exploration [18], text entry [19], gesture-based [20] and multi-touch interaction [21] on smartphones and smartwatches. However, dealing with these touchscreen interfaces poses a number of accessibility challenges [22, 23]. This contributes to an increase in information overload, navigation loss, limited organization/arrangement support, increased learnability, complex discoverability in accessing non-visual items on the screen and operating cumbersome input layouts [24].

Recent research on assistive technologies for blind people is focused on mobility, orientation, pathfinding, identification and object recognition. The innovation in miniaturized wearable electronic travel aids, smart canes, tactical display, interfaces, retinal implants, smartphone-based devices and apps is a newly emerged spectrum assisting people with special needs [25].

In this paper, we have provided a comprehensive review of the research, development and innovation in the field of mobile assistive technology for visually impaired and blind people. We present an insight of past, present and future perspectives, highlight the need for collaboration between medical sciences, computer science and blind people in designing blind-friendly usable, effective and inclusive technological solutions.

This paper is structured as follows. In Sect. 2, we provide an overview of assistive technology for blind people, tasks, challenges and perceptions. Section 3 provides an overview of smartphone-based assistive technologies—an anatomy of smartphone applications for blind people. Section 4 outlines the current state-of-the-art on issues and challenges of smartphone-based assistive technologies in mobility & orientation, obstacle avoidance, access to information, cognitive mapping and knowledge representation in detail, the strength; and weakness of each area is summarized at the end. The issues and challenges in smartphone accessibility spectrum are outlined in Sect. 5. Finally, Sect. 6 concludes the review and sets out future research directions.

2 Assistive technology for blind people: tasks, challenges and perceptions

The domain of assistive technology for visually impaired and blind people is quite complex. There are various perceptions, challenges and viewpoints associated with the technical, operational and administrative management of assistive devices and technologies in orientation, mobility and information access. Therefore, it is very challenging to capitalize on the essence and dynamics of this field within a single landscape. Furthermore, research on assistive technology spans across different diversified disciplines such as computer science, communications engineering, mathematics and mechanical engineering [26].

Blind people are facing severe occupational risks related to their personal safety, hygiene and quality of life [27, 28]. Several hazards, which are easily avoidable by sighted people, are extremely dangerous for blind people or visually impaired people. For instance, an openly uninsulated electric cable is much easier to be avoided by a sighted person; however, the same may be lethal for a blind person to avoid and respond to the situation. Object localization, identification and responding without proper assistive devices are a challenging task for blind people.

Assistive technologies are the collection of equipment, hardware, software, services and products for enhancing the accessibility of an individual and to improve the productivity of an organization, i.e., health institutions, smart homes, etc.[29]. Assistive technology for blind people has actively progressed from performing a simple activity (walking, obstacle detection, etc.) to a complex activity (navigation, shopping, etc.) [30]. People with visual impairment can utilize these assistive technology-driven services and products to perform their daily living activities with more independence resultingly to experiencing an enhanced quality of life. An extensive range of assistive technologies for visually impaired people does exist in the market [30], while assistive technologies with mobile devices are also an emerging trend [15, 25, 31–33]. However, visually impaired people are usually unhappy with the latest assistive technologies, mainly their concern focusing on the production of technology-driven tools [19, 34] rather than tools addressing indigenous requirements and needs of visually impaired people and blind people; thus, these solutions have slim chances of success in real life.

Broadly, uses of assistive technologies are classified into mobility, use of ICT and managing and controlling the user environment through innovative technologies [15]. As a matter of fact, every year more than 23,000 persons loses their sight and register as blind people [35], which not only impacts their daily life activities directly but is also isolating them from society. The emergence of assistive technology and the development of customized tools and processes for visually impaired and blind people in everyday life have greatly improved their productivity [36]. Assistive systems for daily life can be classified in the domains of personal care, time management, reminder tools, food preparation and consumption, finance, shopping, outdoor navigation, home control, etc.[37]. These activities are depicted along with

Table 1 Activities of blind people in performing daily life activities [15]

Activity	Challenge	Risks
Preparing and cooking meals	Food has mold or has passed its use-by date Routine work of boiling water Food is cooked to a reasonable standard	High life risk, fire and hot water Moderate risk of purring hot water Inadequate nutrition ingredients
Maintaining personal care and hygiene	Personal grooming, including shaving, nails cutting, make-up Clothing stains	Moderate risk Hurting own-self Meeting Society standard of living
Staying healthy and managing medical conditions	Health problems, blood pressure, sugar, another disease Medication care Medical Assistance	High risk Proper checkup on time Taking a wrong doze accidentally causing adverse health effects
Cleaning and maintaining a safe home environment	Maintaining safe and livable home environment of daily living Achieving independence Difficult daily tasks including vacuuming, dusting, spotting potential hazards	Moderate to high risk The hard struggling activity of daily nature
Communication and accessing written information	Communicating independently Reading correspondence including collaboration, emails, letters, etc.	Proper and easy to use labeling system Socializing without inadequate gears
Mobility and getting out and about	Encounter disruptions in wheelie, bins and cars parked, pedestrian crossing and mobility in an open environment	High risk to life in an open environment of pedestrian movement in crossing roads and shopping around Risk can be incremented with adverse weather conditions while traveling and moving around
Taking part in social and leisure activities	Social support to engaged Establishment of new relationships, friends Community	Physiological isolation risk Dependency on a personal assistant

their potential challenges and associated risks for visually impaired and blind people in Table 1.

Table 2 lists the needs of blind people in various categories operated indoor/outdoor along with the application needed to assist him in performing several activities.

Blind users confront visual challenges from reading a label on the product to currency identification, navigating into unknown spaces, identifying the appearance of an object or thing of interest [38]. The above activities can be classified in the various sensing types. These sensing types are classified into identification, description and feedback as listed in Table 3.

Figure 1 illustrates the overall flow of the working model of assistive technology for people with visual impairment or disabled people. People with visual impairment interact with these devices, software and the environment through assistive technology. This allows people with visually impairments in performing their daily life activities and experience an enhanced quality of life.

Subsequently, mobile computing, advances in sensors technology, crowed/friend sourcing and data integration capabilities are leading perspectives of smartphone-based assistive technologies [39]. Smartphone cameras play an important role in recognizing objects, in obstacle identification, path identification and path planning [40]. Advances in sensor capabilities have also reduced the barriers of sensing objects through alternative sources. For instance, a GPS [41] receiver is useful in the identification of a particular location in an outdoor environment, a Gyro sensor detects the rotation state of a mobile device in three axes, similarly, accelerometer sensors are helpful in detecting the movement state of a device based in three axes [39]. Screen reader applications and accessibility services (such as Talkback for Android, VoiceOver for IOS) have considerably increased the accessibility of smartphones for blind people [38]. As blind people use sound and touch/vibration as an input stream for performing their various activities, their smartphone can control a wide spectrum of services using touch/vibration and sound intents, thus providing a one-stop platform for blind people to complete their daily routine activities. Smartphones have useful features to disseminate information and service in portable, adaptive, usable and ubiquitous fashion [42]. Table 4 lists common activities performed by blind users along with challenges they may face in each activity in alignment with user interface design and HCI model [43]. These specific requirements include task, domain, dialog, presentation, platform and user model are transformed into specific requirements for blind people [44]. Smartphones present opportunities to deliver an effective demonstration of these services in an innovative and user-friendly manner [33]. Recent advances in smartphone and mobile technologies have

Table 2 Needs, coverage of applications for visually impaired and blind people

Needs	Coverage	Applications	Techniques	Interaction modalities	Type of Solution
Medication	Indoor	Dietary programs Caloric balance Monitoring helping tools for diabetes	Computer vision, Object recognition	Visual, auditory	Markers
Collaboration	Indoor/outdoor	Social networking, Community services, communication	LLA marks, Computer vision, Object recognition	Visual, auditory	Markers markerless
Socializing	Outdoor	Social networking	LLA markers	Visual	Markerless
Outdoor services (navigation, shopping)	Indoor/outdoor	Pathfinding, location tracking, shopping, banking, travel assistance, logistic assistance, infotainment, transportation, orientation	Object recognition, LLA markers, Computer vision	Visual	Markers markerless
Health care	Indoor	Tele-health, tele-care and tele-rehabilitation and e-health Remote management of health cases Health monitoring Fall detection	Object recognition LLA markers Computer vision	Visual, auditory	Markers markerless
Emergency service	Indoor/outdoor	Emergency predication, assistance, prevention	Object recognition LLA markers Computer vision	Visual, auditory	Markers markerless
Learning	Indoor	E-newspapers E-learning and distance learning	Object recognition Computer vision	Visual, auditory	Markerless
Productivity		Alarm system, reminders, caregiver assistance, cooking assistance, drinking assistance, dressing assistance	Object recognition, Computer vision	Visual, auditory	Marker
Food and diet	Indoor	Caloric monitoring, eating, cooking assistance	Object recognition, Computer vision	Visual	Marker

Table 3 Activity base sensing and coverage of activities

Type of sensing	Activity	Example	Coverage
Identification	Object Identification, what are the object primary identifier	What is this? A chair, a tablet? Identifying cold drinks cane Identifying medicine and pills Playing CD of your choice	No context With context description
Description	Visualizing description of some visual or physical property of an object	Own appearance Knowing colors Cloths and dressing, fashion Lighting in the room Device-specific attributes	A similar attribute of an object of interest
Reading and understanding	Access to text	Reading the information in a book Reading email and replying Reading digital display and singe Reading currency classification	Accessing text extracting from objects

leveraged in experiencing the improved quality of life. Smartphone-based assistive technologies provide an ideal environment for application users and developers.

Many researchers have now emphasized the development of a user-adaptive paradigm for designing easy to use, accessible/inclusive and blind-friendly user interfaces based on guidelines for accessible human–computer interaction (HCI) [34, 45–47]. This user-centric approach aims to understand the needs and requirements of the users and to provide the services best developed for their ease and user perspective. The following section provides an outlook on the use of assistive technology using touchscreen technologies in mobile/smartphone devices.

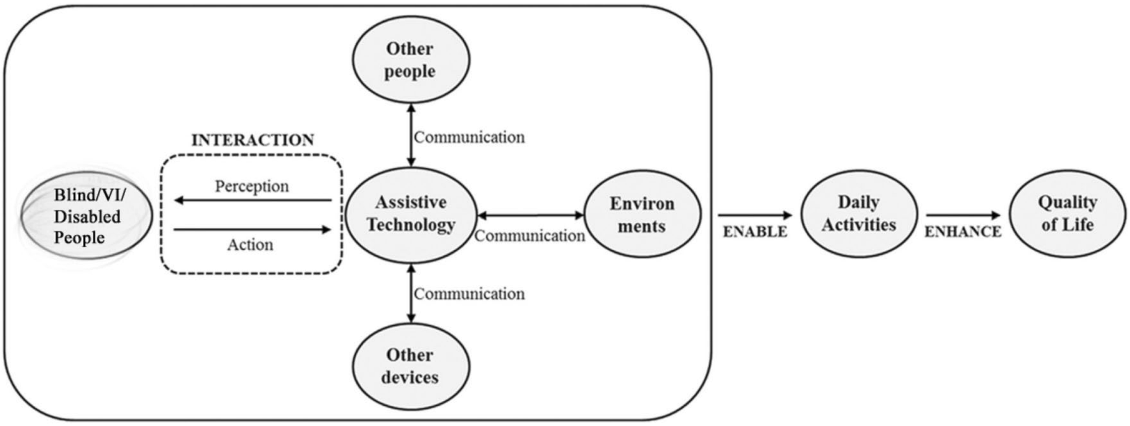

Fig. 1 Diagram of assistive technology working model for people with visual impairment and disabled people [33]

Table 4 Activities of blind people using smartphones

Activity	Challenge	Limitation
Dialing/making call	Finding/locating keys on dialer Wrong touch/invalid touch Dialing/ending call	Dimensional trade-off Task adequacy Behavior equivalence
Sending/receiving message	Finding/locating keys on keyboards Backspace Sentence repetition and correction of sentence	Dimensional trade-off Task adequacy Behavior equivalence
Sending/receiving emails	Security and identify management Finding read/unread emails Smart labeling Reply/forwarding/attachment Maintaining the state/status of the screen Contact management Spamming Degree of importance	Dimensional trade-off Task adequacy Behavior equivalence Semantic loss
Internet surfing	Remembering URL Favorites/bookmarks Finding relevant contents (table data, non-table data, important terms) Navigation Breadcrumbs Skipping irrelevant contents (ads, banners) Form filling/interacting forms	Semantic loss Behavior equivalence
Socializing	Security and privacy Interacting with peers and family Sharing audio resources Identification of non-text-based media (pictures, videos)	Semantic loss Behavior equivalence Task adequacy
Reading text	Locating/identifying text of interest Highlighting relevant contents Reading preferences Repeating a particular sentence/content Understanding pictorial representation	Semantic loss Behavior equivalence Dimensional trade-off
Finding locations	Finding location around you Mobility aids Current context Lack of landmarks Inconsistent usage of tags in the real world	Semantic loss Behavior equivalence Dimensional trade-off
Shopping	Inconsistent tags Identification of products Shopping list Paying products and delivery	Semantic loss Behavior equivalence Task adequacy

3 Smartphone-based assistive technologies: anatomy of smartphone applications for blind people

Smartphone technology has provided a new horizon of opportunities to people of all ages due to its ubiquitous access, portability and accessibility features [42]. Smartphone devices have now made it possible to deliver all solutions (from capturing to feedback) from a single device. Modern smartphones are not just a mobile device or a phone but rather they offer a cluster of diversified features in a compact and portable form [48] and are essentially considered computing devices of high processing power. The touch screen is a vital component of a smartphone, which has replaced the legacy manual controls/ manual buttons and operational hooks in mobile devices thus considerably reduced the device footprints [49]. These opportunities not only are suited well for visually impaired people in operating the touch-based interfaces but also provide freedom in enhanced control over operations such as text entry, text selection, text manipulation using soft buttons of the smartphone. The number of keystrokes is considerably decreased with the advent of text-to-speech systems which are associated with soft buttons or may be operated separately for content reading.

It is important to mention that a growing number of visually impaired and blind people are using a smartphone for performing their daily life activities [6, 7, 50–52]. Researchers have explored innovations in alternative sensory modalities like speech systems [9], auditory [10], and multimodal interaction [11], haptic feedback [12], vibro-tactical [13], gesture recognition systems [14] and have now opened a new era for accessible usage of the smartphone for blind people. Human–computer interaction [53] has contributed a lot in exploring and developing useable and accessible user interfaces for blind people in particular. Though already available applications are not designed specifically for blind people, HCI has specifically defined usability requirements that have to be met when developing user interfaces for blind people with regard to task, domain, dialog, presentation, platform and user models [44]. Eyes-free multi-touch [54] and trackball for gesture control [55] is an emerging research area for blind people in accessing information and providing input for performing daily life activity in an independent manner.

HapAR [56] Handy Intelligent Multimodal Haptic and Audio-Based Mobile AR Navigation system is designed for visually impaired people assisted via Siri (voice recognition). The user can provide commands in voice for locating a point of interest and system step-by-step guidance to the user. The system also provides a haptic alert in case the user diverts from the original path. Touch and Talk [57] allows users to read and edit documents through speech and tactical overlay. This system made available the traditional interfaces more accessible by providing haptic feedback with a stylus or a finger. The pad is the core of the system and may vary in design, providing a tactile model of the screen integrated with a text-to-speech system. The integration of a text-to-speech system enables blind users to reduce their workload on the selection of non-visual items on the screen. BlindSight [58] utilizes the phone's keypad to access the speech navigational menus. All information and confirmations (regarding menu selection, menu items, etc.) are delivered through auditory feedback. Calendar access and adding contacts were the most common in-conversation actions requested by the blind users in this study conducted with nine blind users. These users have pointed out the productive usage of audio feedback in the smartphone-based system.

Accessible design for touch-based interfaces is still a challenge, as the user has to understand the dynamics and orientations of touch screen interfaces. Slide rule [59] provides a talking touch-sensitive user interface for blind users to overcome the accessibility challenge. The multi-touch gesture control system allows users to interact with non-visual objects on the screen. The user scans non-visual items on the screen through their fingers. The sequence of operation of the slide rule system started with one finger scan of browsing list (the system respond the list via the text-to-speech system), the second finger tap for selection of the object or menu item, a multi-direction gesture is used for performing actions and for browsing graphical information a specialized *L-select* gesture. The system was designed to achieve the goal of minimizing the effort for blind users in scanning and responding to non-visual objects/items on the screen through trial-and-error attempts. The study has recommended that multi-touch gestures can increase the accuracy of selection and operating non-visual items on touch screen devices. In a similar pattern, Audio Browser [60] enables blind users to access the information stored in the smartphone through speech and haptic feedback. The soft button on the interface is used for input, while the output is generated in the form of speech. This combination of input/output allows blind users to browse stored information in the smartphone and issue system commands accordingly. The system responds through speech and haptic feedback. The user is guided by speech and non-speech audio as the user move their fingers across the screen, non-visual speech audio is also activated. The system also allows for alerting the user in case of overlapping regions. Within a particular partition, the system informs the user about the information within that segment. The user is further guided about active touch screen area and selection area via speech and non-speech audio indicated the user location on the touch screen.

NavTap [61] is a text-entry system, the main objective of which is to provide an organized and easy to access structure for letters on the keypad. The formation of alphabets is organized in such a way that the user can tap four keys (2,4,6 and 8) on the keypad to navigate through these letters using vowels as anchors, therefore eliminating the need to remember which letters are associated with which key. The solution has reduced the effort of memorization and improved the accuracy of picking the required letters and its associate keys with ease. Multimodal eye-free interaction [62] is an effective alternative to interface design on a smartphone. The information is presented to the users in the form of a 3D radial pie menu, a user has to select an item of interest by following the sound representing that item. Different types of sounds are devoted to representing particular situations resulting in a reduction of task completion time. An evaluation of the system depicted the usage of gestures provides more effective interaction as compared to audio feedback only. MoBraille [63] is a novel framework that enables blind people to use a braille display using an Android phone. MoBraille enables any Android application to interface with a Braille display via HTTP request over Wi-Fi. The Braille display is connected to the Android phone then loads a webpage in a specialized browser to fulfill the requests of the user. MoBraille is a potential application for improving the public transit experience of blind people. BrailleBack [64] is an accessibility service that allows blind people to connect braille devices via Bluetooth. It can work together with Talkback to provide a better experience of braille and speech. Screen contents are presented on the braille display and the user can navigate across keys on the refreshable display. Through the braille keyboard, the user can also input text and interact with the system. JustSpeak [65] is an accessibility service that helps blind users in controlling their Android smartphone through voice command. Once the user activates this service, all on-screen controls can be trigger using voice command. A huge variety of sound patterns are available including commands for open, recent apps, quick setting, on/off Wi-Fi, Home, Back, Notification, Easy Labels, Scroll, Long Press, Switch.

Voice [66] is a utility for Android augmented reality applications for blind users to transform live map camera views to sounds for navigational purposes. The main feature of the application includes color identification (RGB), compass function, face detection and talking GPS locator. In the overall mechanism, the pitch is representing height and loudness for brightness. Voice translates vertical dimension into frequency whereas horizontal dimension into time. HFVE [67] is a vision substitution system enabling users to visualize the images or aspect of images through speech-based sounds and tactile effects. Blind people can add or create images using a standard joystick by hearing-related sound clues. Moving speech-like sounds known as tracers follow the shapes in the images or layouts and convey the sound describing the layout features of the image. All sounds are composed of two styles describing color and layout. The HFVE system has a more enhanced extension having smart features of automated vision processing mechanisms. Similarly, SeeColor System [68] is a sensing vision substation mechanism which transforms low-level visual features into sound. Various models of this system include local/global perception, recognition and alert module. Through hue-saturation leveling techniques, colors are recognized and transformed into moving sounds. The system provides a high level of feedback on any object/obstacle which may harm the blind people through the alert module.

The TapTapSee app [69] helps blind users to identify objects/obstacles in their daily life activities. The system captures photographs from two or three-dimensional object at any angle and the system responds with the identification of the object in audio format. The app includes additional features including repetitions of the last scan available object and the ability to upload images from the gallery and tagging picture with a context. SWAN [70] was developed for blind users for safe and independent navigation and orientation. It is a navigational assistive travel aid providing assistance in customizing GIS data relevant to user-specific needs for wayfinding, obstacle identification and avoidance. It consists of a dedicated interface for tactile input and provides output as audio-only. Once the user location is identified through GPS they system automatically suggest a safe and optimal path for navigation through a set of beacon sounds. The specialized sound used by SWAN includes navigational sounds, object/surface beacon, location and information in pre-recorded sound samples. SWAN purely relies on GIS infrastructure for geocoding of data.

BlindSquare [71] is an accessible GPS app developed for indoor and outdoor navigation. The app utilizes iOS-device GPS capabilities to look up information in the surrounding environment on FourSquare and OpenStreetMap. It describes points of interest, street intersections points and environment information. The system responds to information about user-defined points, intersections and points of interest through a dedicated speech synthesizer. The recent version includes options for check-in, perform searches, adding places and looking around; moreover, Apple Map and Google maps are now also listed as an option for public transport. The application is only available for iOS and iPad users. VoiceMap [72] is a turn-by-turn navigation system for urban areas contributing to independent mobility and orientation using dedicated digital maps. The system helps to find the optimal navigational path; it also continuously monitors the user position and orientation through DGPS. Gesture recognition is used for input; text-to-speech is used to output the voice message and vibration for guiding user.

Smartphones have gained enormous attention and widespread coverage from researchers and industrial scientists to make it more robust, efficient, cost-effective and accessibility-friendly. The above examples illustrate some of the leading works in the field of user interaction, navigation, accessibility, gesture systems and text-to-speech for accessible smartphones usage. The following section is devoted to a more extensive coverage of mobile-based assistive technologies in regard to the strengths and weakness for blind and visually impaired users.

4 Smartphone-based assistive technologies: issues and challenges

Smartphone-based assistive aids are classified into three major categories, i.e., mobility aid [73], control of the environment and use of ICT [33]. Safe mobility and independent living are some of the challenges for visually impaired and blind people to perform daily life activities [74]. Safe mobility demands a combination of temporal and spatial information such as the organization of objects/points of interests, depth perception, context, and user movement [75] and visible landmarks. However, safe travel in an unfamiliar environment is still a challenge although extensive research on mobility and orientation travel aids does exist. The white canes are the most widely used travel aids for mobility, because of their simple, cost-effective and ergonomics design [76, 77]. Remarkably mobile-based assistive technology aids are developed in recent years promoting independent living backed by the development of accessibility-driven interfaces and assistive devices [78]. We have highlighted the impact of smartphones and mobile devices in the area of mobility and orientation, obstacle avoidance, access to information, cognitive mapping and knowledge enrichment in detail in the following sections.

4.1 Mobility, orientation and cogitative mapping

Mobility is an essential aspect of daily life activity for the blind people, who normally rely on prior knowledge of the environment, and objects in the right of the way [79, 80]. Guide dogs and white canes are the traditional assistive travel aids used for decades. Navigating in a complex environment is a challenging activity as, in many cases, the life of a blind person is exposed to risk. Extensive research has been devoted to this area; established solutions and systems provide a significant level of navigation and mobility however have a limited role in addressing aspects of context-awareness and safe travel. The existing solutions are mainly based on the deployment of massive infrastructure (placing tags, pre-fabricated wiring, etc.), moving gigantic devices and real-time understanding of infrastructure layouts. Urban settings are getting increasingly complex; however, the advent of new technologies, existing route planning and identification solutions assist to a reasonable level but fail to provide any safety attention while crossing roads, intersections, etc. Several indoor navigation systems are based on a pre-fixed infrastructure consisting of optical beacons [81], RFID tags, WiFi access points and specialized sensors [82]. Navigation is reliant on the combination of informed decisions of locating users, planning, and identification of path, sensing the environment, identifying buildings, and recognizing objects of interest, etc. A number of technologies are used for determining objects, paths planning and avoidance. The below subsection provides a detailed outlook on these technologies.

4.2 RFID-based interventions

The traditional white canes are made more usable by integrating with RFID technology for reliable movement and exploration [83]. Radio frequency identification (RFID) [84–86] is used to identify and track information of the object of interests embedded in the tags. Electronically stored information is used for the details of an object and environment to support the blind user for navigation. RFID tags are embedded in assistive devices without the need of any source of energy. The tag stores location information and can be retrieved within a proximity of up to 10–15 m. RFID tags are either active/passive or battery-assistive. Active RFID tags have built-in battery sources and periodically transmit their IDs, while passive RFID tags have no battery source, cheaper and smaller. The battery-assistive tags have a small battery installed on board and are activated when RFID reader processes the tag. These tags can be used in conjunction with other assistive aids such as an assistive white cane.

High-Density RFID Tag Space [87] uses a grid density of 1.2 m by utilizing active RFID tags for determining the position of an active RFID grid for deaf–blind people. Similarly, helping hands [88] is composed of RFID readers, microcontroller boards and sound-shield mounted on a special glove worn by the user. The net coverage of this system is from 2 to 3 inches. The SeSAMoNet [89] is a tag-based passive RFID system, integrated with white canes used for navigation purposes. This secure and safe mobility network aims to provide non-intrusive and usable experience to blind and visually impaired users in path identification and planning. The system utilizes color sensor-based RFID helps to follow the color sensors implanted on the ground. The required distance communicated between the tag and user's white cane is less than 5 cm [90]. RouteOnline [91] is an active RFID-based solution that helps blind users to find an optimal route through route selection mechanism. In public transport Bus ID [92] uses RFID tags for sending public transport hotspot information toward the readers. Another attempt is made on an indoor-based RFID system to take advantage of the GPS and Pocket PC to obtain information about user information and the environment. An RFID reader obtains information from embedded RFID tags via the infrared sensor to get travel information [93]. Also, indoor navigation is based on passive RFID fixed in the ceiling of the floor, indicating user position and location on the grid [94]. Table 5 provides an overview of RFID-based intervention for blind people, while Table 6 is devoted to the analysis on RFID solutions.

4.3 Vision Substitution-Based Interventions

Vision substitution solutions take input from the user's surroundings, extract information from images, captions, tags, visual codes, stickers, etc., and transmit information to the user via auditory or haptic feedback [101]. Several vision substitution systems and techniques are developed for navigation and shopping purposes, etc.[102]. However, facial recognition [103], object recognition [104], access to printed material [105] have gained attention only recently.

Barcodes are utilized for identifying and locating the information of an object of interest with the help of a barcode reader [106]. The user has to scan the barcode located at the point of interest during travel or shopping. The system provides information about the user, surroundings and directions details in response to barcode IDs [107]. The method is easy to deploy in closed environments. The emergence of 2D barcodes overcome the limitations of linear barcodes, i.e., one-dimension barcode. 2D barcodes have the capability of storing more information than one-dimensional barcodes. In addition, 2D barcodes host a large amount of information and are capable of handling the diversified type of data such as numeric, text and graphics. QR Code is an extended form of 2D barcode widely used in wayfinding, shopping, medication management, etc. QR Code does not require any power source making it an ideal choice for large-scale deployment in pathfinding solutions. The beauty of the QR Code is the ability to hold geo-coded contextual information for automatic identification, storing and retrieving data using smart devices [107]. In this context, a geo-coded personal assistance system was proposed for the navigation of visually impaired people using the QR Code [108].

Several approaches are analyzed in [109] providing insight into the mechanisms used for identifying non-visual tags and visual stickers. These visual tags differ in shape and capacity of storing information related to the object of interest. The NAVI [110] Navigational Assistance System for visually impaired people utilizes image processing techniques to identify the image. The image captured by vision sensors in the system is re-sized into the 32×32 dimension, while the gray scale of the image is reduced to level 4. Object identification in the image is enhanced by assigning high-intensity values, while the background is suppressed by assigning low-intensity values. The summary of computer vision-based object recognition approaches utilizing the visual tags is adapted from [102] and analyzed in Table 7, while critical analysis is presented in Table 8.

4.4 Sensor-based interventions

The use of sensors has an essential role in reshaping the assistive aids for visually impaired and blind people. Sensing technology has classified the sensors into two types, i.e., active and passive sensors. Passive sensors detect the reflector, transmitted or emitted electromagnetic radiations provided by the natural source of energy. Active sensors provide their energy for illuminations and receive response signals from the object in the scene. Sensing environmental information for obstacles & hazards, providing information, location, orientation, selecting optimal routes toward the desired destination [121] in a cost-effective manner [122]. Inertial sensors, accelerometer and gyroscope are commonly available smartphone sensors widely used for positioning and navigation purposes [73, 123].

Zelek [124] proposed a logical extension of the walking cane providing information to the blind people about their immediate environment via tactical feedback. A special glove provides feedback to blind people. Considerable work has been done on sensing the environment through cheap wearable sensors including 3D accelerometer, magnetometer, fluorescent light detectors and temperature sensors [125]. Sanchez and Torre [126] developed a mobile-based system powered by GPS technology to facilitate visually impaired people in exploring the familiar and unfamiliar environment. The user presses a button to get information about the current location of the user. They can also reach to destination through a text-to-speech synthesizer, hear the information of his/her roundabouts.

Drishti [121] is a precise position management system utilizing DGPS to locate the user's location in the outdoor and indoor environments. A wearable computer, wireless connection and voiced interface help blind people in providing information about routing and re-routing orientation as per the user's latest positions. RADAR [127] is an active sensor-based technique that provides its electromagnetic energy. A radar sensor emits radiations in the form of a series of pulses from the antenna. When the energy reaches the target level, some of them are reflected back, and the distance of the obstacle is calculated accordingly. The advantage of this sensor is the availability of different operating environmental conditions, e.g., day, night, rain, fog and haze. Table 9 provides an outlook of various interventions in sensor-based technologies for blind people, while critical analysis is depicted in Table 10.

Table 5 RFID-based interventions

Intervention/study	Category	Type of tag/sensor	Description	Environment	Use of smartphone
SeSAMoNet [89]	General navigation	Passive RFID	Secure and safe mobility network, micro-chips-based RFID system, the white cane is integrated with an RFID reader for navigation	Real environment	Bluetooth, smartphone voice feedback
RouteOnline [91]	General navigation	Active RFID	Active RFID tags-based system with handheld readers, to find a route to different stations	Real environment	WiFi, smartphone haptic feedback
BusID [92]	Public transport	Passive RFID	RFID tag-based system used to send public transport information to the database and the readers for tracking of public transport services	Real environment	Bluetooth, smartphone voice commands
Blind navigation [93]	Indoor navigation	RFID, GPS, GPRS network	RFID-based system for navigation inside the building. The navigational device communicate with the routing server over GPRS network to determine location information and user's current location concerning the destination	Laboratory	Smartphone, GPS, sound commands
Color sensor [90]	Indoor navigation	Passive RFID	RFID-based navigation system integrated with a white cane. The system follows guidelines for mapping on the floor. RFID tag receiver is installed on a white cane	Laboratory	Bluetooth, smartphone voice commands
Ceiling grid [94]	Indoor navigation	Passive RFID	Ad-hoc RFID tags are used for localization and to determine the position and plan of the route. RFID tags are fixed in the ceiling grid of the floor	Real environment	Smartphone sound commands
Helping hands [88]	Home/class object recognition	Passive RFID	A wearable RFID apparatus used for object identification, it is annotated with the gloves that identify tagged object through sound feedback	Real environment	Smartphone haptic and sound commands
RFID Network Digital Compass [95]	Navigation	Passive RFID	The system is based on voice-commands-based navigation system using a digital compass	Laboratory	Voice commands, smartphone

Table 6 Analysis of RFID-based assistive solutions

Parameter	Description	Analysis
Omnidirectional [88, 96]	RFID tags are omnidirectional and do not require line-of-sight	Easy for blind people to locate the tag and direction. Limited information can be stored thus complicated information can be stored unlike in QR Code
Pre-fabricated structure [93, 97]	RFID tags are to be placed in advance in infrastructure or to be embedded in the assistive gear	Expensive to install a prefabricated infrastructure. Besides, management and maintenance are also difficult to manage and expend. A better solution for limited space or a closed environment. Expending on a large scale is a challenge. Besides it requires specialized hardware to configure and implement
Embedding assistive tags [93, 98]	RFID can be embedded inside assistive devices, dress or clothing	Easy to use with assistive devices. The better solution for smart homes, wearable devices, etc.
Storage capacity [99]	The storage capacity of RFID is quite less, typically, active tag stores 128 KB, while passive tag store is less than 128 KB	It cannot store much information beyond a limited size and cannot process complex information
Blocking of RFID coverage [100]	The human body can block RF signals, and this may also affect the working of RFID in pathfinding	Blocking may result in providing inconsistent information about the point of interest
Short range [89]	The coverage of RFID is within short range (10–15 m)	Blind people need to know the obstacle on the way so they can change their strategy in case of any potential risk
Power source [89]	Active RFID tags require a battery source thus an input source of power will be needed all the time	The power source is one of the dependencies on such a system, the blind people may not all the time know either the system is operational or not
Restricted or close environment [88, 93, 96]	Such systems operate in a restricted environment where the objects are already tagged/deployed	The open environment is still open with many challenges and risks. Alternative techniques such as NFC can be utilized with the rest of the technologies for better solutions

Table 7 Vision substitution-based interventions

Study	Category	Type of tags/sensors	Input capturing mode	Output response mode (Feedback)	User interaction	Description
Badge3D [111]	Navigation	1D	HMD	Voice	Microphone	The tag-based system used for object recognition and obstacle detection. Through Head Mount Display (HMD), video camera sent queries to the system by speaking into a microphone. The user can query the system to find an object nearby
Gude [112]	Navigation	Two barcodes	Two input cameras	Braille	Computer system	Object recognition and navigational system using 2D barcodes, system take input from two cameras (one embedded in white cane, second installed on glasses). Output to the user is communicated through the Braille device
Al-Khalifa Approach [113]	General-purpose	QR	QR reader	Voice	Mobile device	Mobile phone-based QR Code scanning technique, the system transmits a URL after decoding barcode and communicated to the user via verbal instructions
NAVI [114]	Navigation	Computer vision	Optical markers	Voice and vibration	Computer system	User-waist-based system for indoor navigation. The vibro-tactical feedback system warns blind people about the obstacle in the way. Point to point navigations is achieved through optical markers
Looktel [115]	General purpose	Vinyl stickers	Camera	Voice	Smartphone	Visual assistance tool by using computer vision and mobile technology. The live stream is captured from the mobile camera while an object recognition engine computes and processes input streams. Results are communicated through the text-to-speech system in real-time
Google glasses [116]	General purpose	Direction recognition	Camera	Voice, haptic	Smartphone, smart glasses	Equipped with RGB camera and allied sensors, used as a secondary assistive device for blind people

Table 8 Analysis of vision substitution-based assistive solutions

Parameter	Description	Analysis
Processing response [102, 117]	Processing, retrieving responses are not better than the non-tag-based system. The processing depends on various factors such as environment, quality of capturing camera and processing delay	Vision substitution needs robust algorithms to process and retrieve information and present accordingly. Efficient compression algorithms must be capitalized to speed up the delivery of large-sized audio files over 3G networks
Sight of tag [118, 119]	User has to scan every barcode/QR Code on his/her way, which not only slow down the navigational process but also make it difficult to ascertain the exact placement/deployment of barcode/QR labels and tags on the wall or building, etc.	These solutions are efficient for those tasks, which are used to differentiate between related groups, for example, normal signs vs. hazardous signs
Installation and configuration of visual tags [5]	Installation of these visual tags is a careful process and required extensive work on a selection of proper spots, objects, and restricted surroundings, where the objects and environment supposed to be installed	The heavily populated area with visual tags items prone in identifying and tracking the required visual tags
Line-of-sight [113]	Visual tags should be in the line-of-sight with the camera otherwise the camera will not be able to pick the required point of interest	One of the major issues is the line-of-sight of the tag, which is very challenging in the case of an unknown environment
Integration with assistive wears [25]	Visual tags cannot be embedded in assistive wears	An integrated solution provides more responsive results in assisting the visually impaired people
Environmental factors [5, 120]	Computer vision techniques may produce different results due to environmental factors related to imaging, e.g., motion blur, image resolution, video, noise and quality of the visual tag	Modern computer vision techniques are now capable of handling several environmental factors however the results still need improvement. RGB-based image recognition providing better results in identifying particular patterns in the captured scene
Computational capabilities [5]	Computer vision algorithms are typically computationally expensive and thus required a sophisticated processing and memory requirements	The combination of RFID with a computer vision technology will give an edge for solving a number of issues in visual tags

Table 9 Sensor-based interventions

Study	Sensors	Category	Input capturing mode	Output response mode (Feedback)	User interaction	Description
Wearable sensors [125]	3D accelerometer, magnetometer meter, temperature sensors	Indoor navigation	Camera	Assistive belt	Computer system	The fusion of information gathered from different sensors including accelerometer, magnetometer, light sensor and a temperature sensor for indoor navigation
Braille note [128]	GPS, magnetometer, gyroscope	Outdoor navigation, natural terrain environment	Camera	Braille	PDA	A GPS-based system consisting of GPR receiver, software and pulse data, braille note enable users to plan a route, determine the current location, direction and locate nearby locations
Mowat sensor [129]	Tactical vibrations, infrared sensor	Outdoor navigation	Ultrasound waves	Vibration	Handheld	A secondary assistive handheld device uses high-frequency sound to detect objects. The vibration frequency increases as the object approaching
Sanchez and Torre [126]	GPS, bluetooth	Outdoor navigation	GPS entry points	Voice	Handheld	GPS-based navigation system for exploring unfamiliar spaces. The system communicates via a text-to-speech system
Drishti [121]	DGPS, ultrasound	Indoor and outdoor navigation	Ultrasound/GPS	Voice	Handheld, computer	User's position management system, wireless, wearable computer and audio interface to enable blind people to navigate indoor/outdoor. Results show an accuracy of 22 cm
RADAR [127]	Active sensor	Indoor navigation	Signal strength	Voice	Mobile	RF-based system for locating and tracking user indoor movements by recording and processing signal strength of a given point of interest
LoadStone[a]	GPS	Outdoor navigation	GPS input	Voice	Mobile	The GPS-based application enables blind people to import points of interest and promptly inform the user about the location selected

Table 9 (continued)

Study	Sensors	Category	Input capturing mode	Output response mode (Feedback)	User interaction	Description
Intersection explorer [130]	GPS	Outdoor navigation	GPS input	Voice	Smartphone	GPS-based application speaks the layout of streets and interactions and roundabout to the user as he/she touch or drag a finger on the map
Wayfinder access[b]	GPS	Outdoor navigation	GPS input	Voice	Mobile/PDA	GPS-based navigation systems enable users to find locations, plan routes, traffic conditions, announcements and alerts
Mobile geo[c]	GPS	Outdoor navigation	GPS input	Voice	Smartphone	A GPS-based system to find an item of interest on a map. Information is communicated to voice to the user. Compatible only with a smartphone, PDA with Microsoft mobile software
Talking signs[d]	Infrared beam	Indoor navigation	Voice	Voice	Mobile	Uses sound feedback to locate POI and finding the next destinations
SWAN [70]	GPS	Outdoor	Touch	Voice	Smartphone	Customized GIS data are relevant to the specific needs for wayfinding, obstacle identification and avoidance. It consists of a dedicated interface for tactile input and provides an output as voice
TANIA [131]	GPS	Outdoor navigation	Camera and movement sensors	Voice/braille	Tablet computer	It utilizes GPS sensor, tablet computer to provide enhanced precision navigation up to one step accuracy

[a] www.loadstone-gps.com
[b] www.wayfinderaccess.com
[c] www.freedomscientific.com
[d] www.talkingsigns.com

Table 10 Analysis of sensor-based assistive solutions

Parameter	Description	Analysis
Sensor capabilities [132]	The advantage of using sensors includes the ability to measure the distance, speed, orientation, etc. of an object in bad weather and poor environmental conditions	Advances in sensor technology have provided extensive relief in the processing and portability. Modern sensors have generic capabilities of interacting with users in interaction with the environment. For instance, currently available smartphones have more than 13 sensors (Samsung Galaxy, HTC) contributing to high accuracy, reliability and less energy consumption
Interferences with environment [133]	Sensors have different capabilities and limitations in various working conditions. The interferences may lead to disrupting the ongoing operations resulting in creating a risky situation for visually impaired and blind people	Interference with the environment, diversified interpretation of output signals, high & continuous consumption of power sources, poor angular resolution and incapability to detect small obstacles are the challenging prospects of using different sensors

4.5 Sonar-based solutions

Subsequently to the vision, hearing is a vital source for acquiring and responding information, manipulating and coordinating with objects, places and points of interest. Blind people rely on hearing or audio to perceive the environment. Computer users use screen reading software to listen to textual information that appears on that computer monitor and smartphones for reading labels, controls and non-visual items on the screen for example JAWS[1] and Windows-eyes[2] help blind people in operating a computer through the text-to-speech system. A wide array of assistive devices uses audible signals to aid and facilitate the blind people. Audible pedestrian signals are becoming a familiar feature in determining the context of urban auditory environments. Similarly, sonification is the use of non-speech audio to convey information pertaining to a specific object of interest. This localization provides information about the object's in their relative motion. The information encoded by sonification is based on defined parameters of generation and propagation of sound.

The SONAR (sound navigation and ranging) technique [134] utilizes sound propagation to communicate with objects to provide awareness of the surrounding environment. Sonar technology may be active or passive. Active sonar consists of emitting pulses and listening for echoes, while passive sonar listens to sound without transmitting. The omitting frequency may range from infrasonic to ultrasonic depending on the nature of propagation. Sonic Path Finder[3] uses a sonar system to detect objects while walking. User distance can be computed from the echoes, while the same is communicated to the user through varying tone pitch. KASPA [135] Kays' Advanced Spatial Perception Aid is a complex type of sonification system consisting of sweep FM ultrasound emitter and displaced sensors. The echo signals are transformed into audio sounds by providing information about the range and reflective properties of the object.

VOICE [136] is a sonic imaging system that uses digitalize imaging in sonification by transforming x-coordinate of the image into time, y-coordinate into frequency and gray scale into loudness resulting in a complex dynamic sound with chords. Echolocation [137] is the ability to sense objects for echoes. The process of echolocation consisting of sending a sound toward an object of interest and recording timing in return. Researchers have contributed extensively to developing new algorithms in the area of echolocation. Table 11 depicts several research studies in the area of the sonar-based technologies for blind people, while Table 12 shows analysis of these studies.

4.6 Augmented reality-based solutions

Augmented reality [142–144] has made significant achievement in the past decade. One of the main driving forces behind its development and success is the enhanced processing capabilities, incorporating sensors and rich multimedia features.

The latest smartphones are equipped with a high-resolution camera, touch screens, sensors such as accelerometers, GPS and compass making this device a single source of providing all kinds of services to blind users in one place. The current generation of smartphones is sufficiently powerful to render multiple audio/echo-location for blind people co-powered by other allied sensors including GPS, compass,

[1] https://www.freedomscientific.com.

[2] https://www.gwmicro.com.

[3] https://www.sonicpathfinder.org/.

Table 11 Sonar-based interventions

Study	Category	Type of sensor/tag	Nature	Input	Output	User interaction device	Description
Sonic pathfinder [138]	Navigation	Sonar based	Signal device	HMD	Voice	Micro-computer, HMD	Head-mounted pulse-echo sonar system operated through a microcomputer, three receivers (one pointing left, one right and straight ahead) and two transmitters developed for wayfinding
Miniguide [139]	Object identification	Echo-location/ ultrasonic	Signal device	White cane sensors	Vibration	Handheld	It uses ultrasonic echolocation to detect objects. It vibrates to indicate the distance. It is used as a secondary mobility aid and provides feedbacks through sound commands
Ultracane [140]	Object identification	Sonar-based/ ultrasonic sensor	Signal device	White cane sensors	Vibration	Dedicated device	Ultrasonic waves are used to detect objects, drops-offs, stairs through traditional touch techniques. Based on the time gap between transmission of the ultrasonic wave and detection of transmitted echoes and distance/speed
Guide cane [141]	Navigation	Sonar-based/ultrasonic sensor	Signal device	Ultrasonic sensor	Vibration	Computer	Guide cane provides acoustic signals via a set of stereo earphones that guide users around obstacles through an ultrasonic sensor mounted on the sensor head
VOICE [66]	Navigation	Sonification	Sound device	Camera	Sound	Smartphone	A sonic imaging system in which digitalized imaging are sonified by transforming the x-coordinate of the image to time, y-coordinate to frequency and gray scale to loudness

Table 12 Analysis of sonar-based assistive solutions

Parameter	Description	Analysis
Echo capabilities [138]	Sonar technology has a potential prospect of object identification and recognition on the pattern of sounds/echoes reflected from objects, containing information about geometry, size, orientation and surface material properties of the reflectors	This technology has the capability of operating in a dark environment. Moreover, information about the object is far behind the physical reach of the users, resulting in an alert to the user about the obstacles in his path, which cannot be achieved with the help of traditional travel aids
Complex environment [66]	Sonar Technology is not very effective in the indoor environments for instance mixed, and coupled objects may present reflected echoes resulting in the projection of unreliable information communicated to the users	The device can be conveniently carried by the users and does not require the installation of sensors, tags, etc. on an environment as required in RFID. Sonar can be used effectively for organized objects or places
Overloaded [139]	Sonar works well for recognizing rough objects, but they may respond poorly to objects with smooth or angular surfaces. Furthermore, the blind people usually are overloaded with so many sound commands which are mixed up with environmental voices	The audio-vision substitution system also overloads the auditory system and reduces his/her capacity to hear sounds in the complex or outdoor environment (e.g., open to traffic, walking, etc.). Similarly, these devices are not used in public places, as they reduce the ability of blind people to detect danger from sound or noise

etc. The majority of augmented reality applications have focused on visual modality, overlaying virtual objects on real-world scenes through live camera feed on a mobile screen; however, blind people can benefit only through voice or haptic responses. Audio augmented reality [145] is useful for blind people for perceiving the real world through audio interfaces. Intersection Explorer[4] is an Android smartphone application that helps users to explore nearby streets and intersections by dragging their figures on the touch screen. However, spatialized audio has been employed in a number of studies, for example, personal guidance system [146] which uses GPS, compass and spatial speech to guild blind users by rendering round-about points of interest either by proximity or presented in clockwise fashion [147]. MoBIC [148] is a similar system like PGS. ISAS [145] is an application allowing blind users to explore urban areas without having a particular destination in mind. Lorenz et al. [149] proposed an augmented reality system for representing building information models(BIM) including doors, rooms, etc. through specialized labels. Different access points are defined to reach another floor or switching between rooms. The system uses a graph hierarchy algorithm to represent node points like rooms, doors, etc. for navigation.

4.7 Cognitive mapping

The life of blind people is moving around the perceived knowledge of their surroundings by recognizing orientation attributes like identification of structures, walls, angles of the room in the indoor environment [150], etc. They are dependent on their ability to make an informed decision related to a situation through their cognitive ability to use other sensory capabilities [151]. Blind people interact with environment through visual alternative sensory such as voice, gesture and touch. Such kinds of interactions are composed of a sequence of psychological transformation to acquire, store, recall and code/recode information about a location or object of interest is known as cognitive mapping [152]. The researcher illustrated that the support for the acquisition of mapping should be supplied either at perceptual or conceptual levels [153]. At the perceptual level, visual information is compensated by other senses including tactile or auditory information, whereas at a conceptual level the main focus is on the development of strategies for an effective mapping of open spaces items and generation of navigational paths. ICT-based assistive aids are greatly supporting blind people in exploring new spaces [154]. These assistive aids are of two types, i.e., active and passive aids. Passive aids provide

[4] https://www.googlelabs.com/show_details?app_key=agtnbGFiczIwLXd3d3IVCxIMTGFic0FwcE1vZGVsGIHDtwIM.

Table 13 Cognitive mapping-based solutions

Intervention	Category	Orientation	User interaction	Gestures	Description
Space sense [117	Indoor /outdoor navigation	Active	Handheld	Yes	Map-based navigational assistance for planning future trips based on the perception of reality
LocalEyes [41]	Outdoor navigation	Passive	Smartphone	Yes	Multimodal-based navigational and awareness application for exploring open point of interests
Reconfigure mobile android phone [156]	Outdoor navigation	Active	Smartphone	No	Audio feedback enabled system senses and capture the environment data in the form of an image converted to audio
MobileEyes [156]	Indoor/outdoor navigation	Active	Smartphone	No	Helps blind people to see and understand their surrounding environment during travel and can perform other activities using the mobile phone via text-to-speech system
NOMAD [159]	Outdoor navigation	Active	Braille/touch	No	Uses touchpad placed under a paper-based braille map to detect which part of the map is contacted by blind people. The system generates audio feedback to the user about information related to contacted points

information to the user before his/her arrival to destination, for example, tactile maps, physical models and strips maps. Active aids provide information to users on-site at runtime, for example in the Talking Sign application the sensors are embedded in the pre-fixed infrastructure [155]. However, active and passive aids have several limitations such as low information coverage, inadequate symbolic representation, error aspect ratio in distance calculation and cluster size. Reconfigured Mobile Android Phone [156] provides support to the blind people in performing their daily life activities through audio feedback mechanisms. The system captures the environment in the form of an image and extracts text from the captured images. The application works well even for complex activities such as exploring a route map. MobileEyes [156] enables blind people to see and understand their surrounding environment. Similarly, LocalEyes [41] is a multimodal interface layout to facilitate visually impaired people in navigation and context-awareness. The user can also explore information about coffee shops, restaurants and surrounding points of interest.

Navatar [41] allows visually impaired and blind users to facilitate localization and navigation with the help of physical characteristics of the indoor environment. User locations are estimated using an accelerometer sensor and tactical landmarks. SpaceSense [157] is another map-based application for handheld touch screen devices supported by taps and flick gestures. This helps blind users to learn about the environment on-site and enhance their cognitive mapping of the area in focus. With the help of this app, the user plans for future trips. The system also offers high-level information about distance and direction toward a destination or a particular point of interest. Marston [158] illustrated that blind people can navigate an environment faster using a continuously generating beeping 3D sounds encoding direction to the next point. Table 13 lists cognitive mapping solutions for visually impaired and blind people.

4.8 Semantic augmentation: knowledge representation for blind people

Comprehending information pertaining to unknown spaces, landmarks and points of interest is a challenge for blind people. The quality of effective and safe navigation is critically dependent on spatial modeling of the navigational spaces around. Various data representations are proposed for spatial modeling including geometric models, graph theory, symbolic representation and hybrid approaches [160]. Geometric models representing navigation as the coordinate system and mainly supporting geometric queries like roundabout places, whereas symbolic models represented through symbols, inter-symbol relationship and semantic relation between the symbols. The basic aim of using semantic annotation is to answer queries like awareness of spatial semantics, awareness of navigational context, response to user or space with a change in context. Sighted people can view the environment and judge its complexity by moving around inside the building, rooms and other desirable points of interest. The same is very challenging for blind people to navigate across the landmarks, obstacles in the way [161]. Karimi [162] proposed a smartphone-based universal navigation system which uses spatial data on the end nodes, all point of interests are retrieved from a navigational data source.

Graph hierarchy algorithm [163] uses access points to represents floors and edges showing labels for the presentation of rooms, corridors, doors and pass ways. However, the main issue in the above approaches is that building information needs to be collected from the building owners and systemic information needs to be uploaded to the system to generate a usable map for blind people to navigate accordingly. Location can be expressed at a different level of granularity and users should be able to use location items such as cities, buildings, rooms and so on for the said purpose these symbolic locations should be encoded in ontologies [164]. These ontologies explicitly represent the properties of the locations and their relationship. Moving object ontology [165] purposes formalized movement patterns and retrieve trajectories. However, the scalability of MOD is still an open issue. The SeMiTri [166, 167] system consists of a stop/move computation part that processes raw GPS records to produce the output trajectory in the form of a shop or moves. The semantic annotation part of the system includes annotation layers for representing the region, line and point, generating an annotated trajectory, trajectory patterns.

4.9 Obstacle detection/avoidance

The white canes are the most usable mobility aid for visually impaired and blind people in detecting obstacles and avoiding accordingly [141]. The white cane is an inexpensive assistive aid that requires user training and awareness to scan objects ahead, side by side and round-about is more consumption. Researchers have introduced an advanced navigational system for identifying and avoiding obstacles. Smart Vision [168] is a navigational aid which electronically enhances the white cane's capabilities to guide the user to reach to the destination while avoiding an obstacle on the same route. Smart vision supports local navigation by path tracking, obstacle detection and covering area from the front and beyond the reach of the white cane. Calder [169] has developed a prototype-based ultrasound system for warning users about an obstacle in their path. The system utilizes the tactical display as a substitute for a long cane. Vibrations are used to inform the user about obstacles across the path, whereas the object is detected through system generated audible sound. In the same pattern, Zhang [170] has developed a hands-free device to complement the white cane. A sensor unit is incorporated underneath and at the front of the user's shoe for detecting road surface reflectance and obstacles. The system alerts the user through vibration signals.

Navbelt [141] is an assisted belt assembled with ultrasonic sensors to provide auditory feedback to visually impaired people. The response of obstacle detection is communicated via headphones (voice) to the user. The visually impaired person experiences audible feedback indicating safe path to travel in case of no obstacle detects on the way, while the volume of audio feedback increases in the inverse proportion to the distance to an obstacle ahead. In the smartphone-based object detection system proposed by Peng [171], the user walks with a smartphone held at 45-degree tilt angle, until the phone vibrates to indicate whether the path ahead is safe or not. The system provides verbal options to indicate which side is safe to move and the user can plan the remaining path according to their needs. Haptic responses are emerging feature to help blind users to avoid obstacles. Amemiya [172] proposed a haptic direction-based system developed by pseudo-attraction force technique [173]. The force produces sensation by exploiting human perception characteristics. The main advantage of the force sensation is to prevent the overuse of audio feedback. Intelligent glasses [174] are a non-invasive navigational aid that converts visual data into tactile representation via a computer vision system. The tactile representation is displayed on a touch stimulating surface. A camera mounted on the glasses frame detects an environmental obstacle and translates this information into haptic feedback that is presented via tactile display carried by the users. Table 14 provides a detailed overview of research interventions in obstacle detection and avoidance.

4.9.1 Access to information/media/non-visual items

The ability to communicate and collect information from all over the world from their home or workplaces has extended the opportunities for blind people to participate in society more effectively [176]. Sighted people have access to utilize the visual impression of every media; however, blind people have limited options available to access the text, convert the text to speech or haptics.

Blind people face a number of issues in accessing smart interfaces, for instance, accessing textual information, graphics, maps, 3D and visual environments. Mostly, blind and visually impaired people have to depend on television, radio or information that can be speak-out. The smartphone is the success story of the decade not for sighted people only but also for blind people as well. These technologies have penetrated significantly in society and considerably improved the effectiveness and reduce the cost of traditional approaches for performing common activities of blind people.

Blind people face some issues in accessing touchscreen interfaces, for instance, accessing textual information, graphics, maps, 3D and visual environments. These technologies have penetrated significantly into society, considerably improved the effectiveness and reduced the cost of traditional approaches for performing common activities [176]. Through a series of studies, researchers have identified recommendations for browsing, text to speech, screen orientation, screen partition, and how effectively locating the object of interests on touch-based interfaces for enabling blind people to interact with mobile technologies for performing their common activities. Table 15 provides a summary of accessibility-inclusive interventions.

Table 14 Obstacle avoidance/detection interventions

Intervention	Category	Tags/sensors	Input	Output	User interaction	Description
NavBelt [141]	Navigation	Ultrasonic sensors	Ultrasonic sensor	Voice	Assisted belt	An assisted belt assembled with ultrasonic sensors to provide auditory feedback to blind people enable them to avoid obstacles and navigate safely
Guide cane [141]	Navigation	Sonar-based/ultrasonic sensor	Ultrasonic sensor	Vibration	Computer	Guide cane provides acoustic signals via a set of stereo earphones that guide users around obstacles through an ultrasonic sensor mounted on the sensor head
Ultracane [140]	Object Identification	Sonar-based/ultrasonic sensor Signaling device	White cane sensors	Vibration	Assisted cane, white cane	Uses ultrasonic waves to detect objects, drops-offs, stairs through traditional touch technique. Based on the time gap between transmission of the ultrasonic wave and detection of transmitted echoes and distance/speed
Smart Vision [168]	Path detection, path planning	Wi-Fi, GIS (indoor) GPS (outdoor) RFID (fail-safe environment)	Stereo camera	Voice	Portable computer	Wearable navigational aid for local navigation in indoor and outdoor, detection of path borders and obstacle in front. Using a stereo camera worn on the chest, backpack computer and responses are communicated via voice
Zhang [175]	Road surface and obstacle avoidance	Wearable sensors	Camera/kinect	Voice	Smartphone	Wearable navigation system, utilizing a floor plan map as a semantic plan. The landmarks and points on these maps are extracted and used in the framework for navigation
Peng [171]	Obstacle detection, path safety, path planning	Smartphone sensors, RGB	Camera	Vibration/ Voice	Smartphone	A real-time obstacle detection system for mobility using a smartphone, the system detects any object on the floor irrespective of its height
Amemiya haptics [172]	Navigation	Pseudo-attraction force	Kinesthetic perception	Haptics	Mobile phone	A haptic indicator to help blind people in mobility and orientation using a pseudo-attraction force

Table 15 Summary of accessibility-inclusive interventions

Intervention	Category	Capturing input	Output response	User interaction device	Gesture	Purpose
Voice over [177]	Contents and controls	Screen contents and UI controls	Voice	Smartphone	Yes	Voice over is an accessibility service for Apple iPhone, iPad enables blind people to read-out content and UIs labels on the screen. Voice over gesture uses one, two-finger to drag, tap and flick
Mobile speak [178]	Contents	Screen contents	Voice/vibration	Smartphone	Yes	This screen reading application generates and translates contents of the screen to the speech and Braille display
Talkback [179]	Contents and controls	Screen contents and UI controls	Voice	Mobile/smartphone	Yes	This enables blind people to read the content through the text-to-speech system. The users explore the screen either through swipe and tap gesture while receiving audio feedback too
HearSay [180]	Contents, non-visual browsing	Web contents	Voice	Web, PC	No	A voice XML-based non-visual web browser to read web page contents intelligently by avoiding adverts, banner, etc.
Borodin et al. [181]	Tele web services	Screen contents	Voice	Mobile phone	No	Tele web services used to access the web, check email and operate the phone
Chu et al. [182]	Contents	Screen contents	Voice	Web, PC	No	2D interactive voice browser for reading contents of web pages
Ghose et al. [183]	Contents	Screen contents	Voice	Web, PC, mobile	No	An open-source browser architecture allowing blind people to navigate websites through voice commands
Talking touch [184]	User interaction	Screen contents	Voice	Smartphone	Yes	A touch-sensitive UI design to overcome the accessibility challenge. The user scans non-visual items on the screen through their fingers and receives a response in the form of voice
Project ray [185]	User interaction	User Input via finger	Vibration/voice	Smartphone	Yes	Locating digit keys on screen for dialing purposes, they have proposed their letter placement layout scheme
Young et al. [186]	User interaction	Braille self-adhesive plastic	Voice/vibration	Smartphone, braille	No	Typing braille letters and sending messages for identifying the key positions on the touchscreen. A self-adhesive plastic installed on the screen
Mascetti et al. [187]	User interaction	Braille input	Voice	Smartphone	No	Typing braille letters on a smartphone by touching fingers on the interface, supported by a QWERTY keyboard
Jayant et al. [188]	User interaction	User input	Vibration	Smartphone	Yes	Application for displaying of grade 1 Braille on a smartphone screen, they have divided screen into six parts called dots in Braille language and represented numbers from one to six dots
Bonner et al. [189]	User interaction	User screen input	Vibration	Smartphone	No	12 keys virtual board, fixed-layout for selecting the right points of interest

Table 15 (continued)

Intervention	Category	Capturing input	Output response	User interaction device	Gesture	Purpose
No-looks notes [189]	User interaction	Text-entry user input	Vibration	Smartphone	No	An eye-free text-entry system on a touchscreen platform. The device screen is divided into 8 segments and further divided into one group and 26 character
Slide rule [59]	User interaction	User gesture input	Vibration	Smartphone	Yes	Multi-touch interaction associated with different actions associated with touch items
Touch player [190]	Integration and User Interfaces	Gesture Input	Vibration	Smartphone	Yes	Based on directional gestures and non-speech feedback
Braille Touch [191]	Interaction and user interfaces	Gesture input	Vibration	Mobile phone	No	Eye-free touchscreen text-entry mechanism used for educational purposes
MessagEase [192]	interaction and user interfaces	Gesture input	Vibration/voice	Smartphone	Yes	Using tapping and sliding techniques for interacting with the contents
NavTouch [61]	Interaction and user interfaces	Gesture input	Voice	Smartphone	Yes	The user can perform gesture interaction anywhere on the screen

4.9.2 Selecting non-visual items, interface and UI controls

Recently, touch-based interfaces have had a great impact on the emergence of the mobile communications market. Due to the absence of tactical cues, some researchers have struggled hard to make these devices more accessible for blind people. A large display surface with an ability to create visual interaction components has gained the opportunity for interaction with touch screens by blind people.

Extensive research is devoted to on-screen reading and capturing activities. Screen reading software applications have been developed for assisting blind users to read the contents of the screen on desktop as well as on mobile devices/smartphones. Applications, such as JAWS, NVIDA, Narrator[5] of windows, Metal mouth,[6] Windows Eye, Desktop, Talkback, Sound back,[7] Mobile Speak[8]and voice-over,[9] provide assistance to understand every single piece of text on the screen. Many scholars have demonstrated the development of assistive tools with the latest technology [193] which includes the development of text-to-Braille systems [194–200]. The use of ASR (automatic speech recognizer) enables blind people to convert speech-to-text [201].

Zhang and Liu [202] have discussed the difference between smartphones and feature phones noting that smartphones have suppressed traditional phones by designing feature phone-enriched user interface elements such as the screen size, and multi-touch and sensing intelligent objects. They have concluded that user interface and built-in sensors ensure feature phones boast faster development and enhanced interaction. Krajnc et al. [184] presented a concept of a new type of user interface for blind people in which the touch screen has no tactical on-screen clues to help in identifying keys and UI components. In this way, blind people can interact with smartphones easily; they have suggested a "talking touch" view such as "talking touch list" this list is composed of a set of pages allowing blind people to input faster with audio feedbacks.

Aaron [185] presented "RAY Project" in which the issue of identifying the center point of touch screen is fixed in response to user's touch. The user fixes a point on the touch screen, the touch-point is considered as center of the screen, in this scenario, it is represented by digit 5, whereas the rest of the digits are accommodated on left/right sides. The top

5 https://marinersoftware.deskpro.com/kb/articles/281-what-is-narrator.

6 https://code.google.com/p/metalmouth/.

7 https://play.google.com/store/apps/details?id=com.google.android.marvin.talkback&hl=en.

8 https://webcache.googleusercontent.com/search?q=cache:mhUrXg4ZEWYJ:www.itu.int/ITU-D/sis/PwDs/Documents/Mobile_Report.pdf+&cd=1&hl=en&ct=clnk&gl=pk.

9 https://www.apple.com/accessibility/osx/voiceover/.

center represents as digit 2, top left represents digit 1, top right represents digit 3, left side from center represents digit 4, right side from center represents digit 6, bottom left represents digit 7. The bottom center represents digit 8, bottom right represents digit 9 and the bottom of these three digits represent a symbol of starting 0 and hush in sequence from left to right. Young et al. [186] made an application for typing Braille letter and sending a message through Braille typing application. For an easy interaction, they have proposed a "self-adhesive" plastic which has holes for identifying the keys positions in the screen according to their application. Mascetti et al. [187] developed a "Type-in-Braille" application for typing Braille in the smartphone screen by touching fingers. This solution overcomes the limitation of mental workload and time-wasting on connecting a Braille display with a Smartphone. Jayant et al. [188] developed an application for displaying of grade 1 Braille on the smartphone screen. They have divided screens in six parts called dots in Braille language and represented numbers from one to six. This combination of on/off dots among these six numbers represents one character. Bonner et al. [189] presented a 12-key virtual keyboard approach. This layout is fixed and consisting of a pie menu with eight options, which can be read upon touching the screen. Overall, attention has been given to touch input for selecting and locating the right point of interest on the right time, illustrating potential for low cost mainstreams devices to provide accessibility and productivity.

4.9.3 Surfing contents/maps and graphics

With the advancement of text-to-speech engines in web browsers and common applications using the voice synthesis interfaces are becoming more popular in reading content and screen items. Special screen reader software like JAWS,[10] NVDA,[11] SuperNova[12]and Window-Eyes[13] have been given preference over built-in screen reading. Borodin et al. [180] have developed the HearSay a voice XML-based non-visual web browser for blind people, reads the web page contents in two navigation mode continuous reading and passing, while extra information like banner, menus, adverts, etc. are skipped in a web page. The browser also provides menus that contain a list of visited and unvisited links. Chu et al. [182] proposed two dimensions of interactive voice browsers whereas they have integrated voice functions. IBM Chinese text-to-speech synthesizer was embedded to speak loud all web contents. The browser is based on IE running engine on windows platform. This browser reads the structure of web page elements including frame, table, links, menus and forms at the startup. Coding numbers are assigned to the section of a web page in increasing order which normally starts from one to the end. However, the solution raised issues in punctuations and special characters. Borodin et al. [181] introduced tele-web services integrating a simple and usable phone interface with the help of intelligent context-directed browsing. This helps blind people to access the web though a phone and can search the web and check their email and other web activities by speaking and using phone keys. This system was initially developed for desktop users. Ghose et al. [183] proposed an open-source browser architecture allowing blind people to navigate web sites trough voice commands. This architecture supports text-to-speech and text-to-Braille and keyboard operations through voice feedback. Considerable work been down in browsing contents however identifying relevant contents, skipping adverts and translating multi-lingual contents are still a challenging opportunity.

4.9.4 Text-to-speech system

Enhancing accessibility is a demanding requirement for blind people. Screen reading applications provide wide facilitation, translating content to voice has a potential aspect despite their limitations. Talkback and Soundback[14] is an accessibility service which accesses smartphone content and controls easily, through voice and vibration feedback from the contents and UI controls of the smartphone.

Mobile Speak[15] is a screen reading application for blind people which generates speech from all displays contents of the screen through text-to-speech and text-to-Braille (if the Braille display device is connected to a smartphone). Voice Over[16] is another gesture-based screen reading application for blind people. The user can scan the screen by dragging the finger on the screen, and read out the contents of the screen, text in the textbox, having the facility of converting screen contents to Braille display if Braille display is connected to a smartphone.

4.9.5 Accessibility of mathematics and videos

Presentation of the structural information contained in shapes, complex graphics, motion videos and mathematical formulas is a major challenge for visually impaired people

[10] https://www.freedomscientific.com/products/fs/jaws-product-page.asp.

[11] https://www.nvda-project.org/.

[12] https://www.dolphincomputeraccess.com.

[13] https://www.gwmicro.com/Window-Eyes.

[14] https://play.google.com/store/apps/details?id=com.google.android.marvin.talkback&hl=en.

[15] https://en.wikipedia.org/wiki/Mobile_Speak.

[16] https://www.apple.com/accessibility/ios/voiceover/.

[203]. Blind users are using voice presentations; however, a typical linear presentation with the voice may be ambiguous to understand the complexity of these complex activities. Access to mathematical formulas and equations is partially resolved by the digital accessibility information system (DAIS) standard (ISO/ZNO R2012 specification for Digital Talking Book) [204]. Furthermore, MathPlayer [205] reads aloud the mathematical formula prescribed in MathML notation. MathJax [206] is a Javascript library for visual rendering of a formula created in MathML, Latex and ASCIIML. Multimedia content such as video is constantly increasing on the web and mobile. This content can be made accessible by utilizing the Web/Mobile Content Accessibility Guidelines [203]. Federico [207] proposes an architecture that automatically creates captions for video lessons by exploiting advances in speech recognition technologies. Wald [208] developed a tool that allows crowdsourcing correction of speech recognition captioning errors to be used in order to provide a method to make video accessible to the visually impaired people. The audio description technique is to provide access to the media contents to the blind people. Video audio descriptions are composed of recorded text pronounced by the actors aligned with gaps and timelines in the original soundtrack of the video [209].

4.9.6 Touch and Gesture-based Solutions

Gesture-based interaction techniques have been introduced on touch screen devices recently. Some of the operations include flicking, rotating, flipping, flat hand, the horizontal hand is a few single and multi-finger gesture is available in the smartphone [210]. Slide rule [59] uses multi-touch interactions to make touch screen accessible for blind users, through a set of multi-touch interactions associated with their functionalities. Similarly, Touch player [190] provides directional gestures and non-speech feedback to blind people for interaction purposes.

Braille Touch [21] which is an eye-free text-entry mechanism is designed for touch screen mobile devices and can be used for educational purposes. MessagEase [192] uses the slide and tap model for touchscreen-based text entry. The selection of primary characters in a layout is performed via tapping, while the secondary layout menu can be explored by sliding toward certain directions. NavTouch [61] is a gesture-based interface where users can use gestures anywhere on the screen providing benefit of extended interface and layout. Gestures to left and right navigate alphabetically in both orientations (horizontal and vertical), vowels are used as intended letter whereas speech feedback assists a user in navigating the alphabets.

4.9.7 Analysis of access to media, text and videos

Smartphones provide opportunities for blind people to access information via text-to-speech or Braille systems in a usable manner. Several systems, solutions, techniques and interaction paradigms are being developed for blind people [211]. Communication through these electronic aids has provided new possibilities for blind users. However, several enhancements in the interaction paradigm need to be incorporated. One of the significant disadvantages of touch-based interfaces is the missing tactical clues [55]. Identifying a widget or navigational buttons within an interface can be a challenging task for the blind. In addition, interaction via voice suffers from inherited issues of poor performance, noisy environment and change of ascent, thus resulting in increasing mental load and memorizing voice instructions may detriment user privacy in open environments [212].

The tactile sense is another missing factor in touch-based interactions, besides, overlaying virtual control degrades touch sensing capabilities [213]. Another problem that blind people experience is locating non-visual objects, overlapping regions, borders and adjustment objects on the touchscreen. The potential of touch-based interfaces can be achieved to a great extent while addressing the eight generic rules of Shniderman [214] for user interface design. These include consistency in design and controls, offering immediate feedback (tactical or auditory), offering an error handling, and error prevention, reducing memory overload, providing an option for a home back in case the user lost his path for action or performing an activity.

5 Smartphone accessibility spectrum: issues and opportunities

Touchscreen interfaces have a significant impact on the emergence of the mobile communication market. Due to the absence of tactical cues, physical control and buttons, researchers are struggling in making these devices accessible to the blind. The ability to create visual interactions on large displays introduced an opportunity for blind people. Several interaction capabilities through audio and haptic interactions in user interfaces are already available in commercial products. These opportunities help blind users in operating the touch-based interfaces by providing them enhanced control over the operations such as text entry, text selection and text manipulation.

The user-centric approach aims to understand the needs and requirements of the users and provides services best developed for their needs. Blind users avoid content when they are aware in advance that this will create accessibility problems [215]. Similarly, the level of frustration increases, whey they have to process poorly labeled links, forms elements, missing or misleading alternative text for the graphical image, notation or graphics by using screen reading software [216]. Moreover, sighted people consume 66% of their time in editing and correcting text on an automatic speech recognizer output on the desktop system [178].

Although the human–computer interaction (HCI) field [53] has developed usability and accessibility guidelines in developing usable and accessible user interface for blind users, a number of mobile applications still remain inaccessible for the blind [44, 217]. Many researchers have now emphasized the development of a user-adaptive paradigm of designing simple to use, easily accessible and user-friendly user interfaces based on the guidelines of HCI [34, 45–47]. The latest interventions such as eye-free multi-touch interactions [54] and trackballs for gesture control [55] are emerging research areas in accessing information and performing daily life activities in an independent manner. Smartphones have useful features to disseminate information and service in a portable, adaptive, usable and ubiquitous manner [42]. The imperfections in the existing user interfaces have been addressed by emerging technological solutions and alternative forms of input, output and interaction [17]. Researchers and practitioners have conducted studies in identifying, mapping and recommending the effectiveness of user interfaces into the mainstream HCI paradigm [218]. A number of usability concerns from the perspective of blind people in the context of universal user interfaces are presented in the following.

5.1 Inconsistency in interface elements

Consistency refers to the naming, labeling and structure of commands, in such a way, that the user does not need to remember the commands for the similar tasks in an application or layout. Currently available interfaces have limited persistence and consistency, due to which, it is difficult for blind people to remember every action on the screen [219]. In addition, existing mobile applications offer diversity in look and feel, design aesthetics, layouts and navigational schemata. Even, a common mobile action such as placing a call has divergent screen interfaces in different calling services such as Skype, WhatsApp or Imo applications. This inconsistency in the design rationale leads to an increase in learnability and discoverability in performing common activities on smartphones [37, 220].

5.2 User interface flexibility

The adaptability to accommodate user requirements into a holistic preview is a vital limitation in the existing user interfaces. Every interface should provide meaningful entry and exit paths presenting a case to accommodate user experience, capabilities and skillset. The user interface's transparency and plasticity are vital determinant issues [221].

5.3 Logical orders of items and navigational items

The interpretation of content, UI elements and non-visual items in a logical arrangement is an issue. Blind people are misled in the understanding of contents if presented in the wrong order. The issues are amplified further, if the number of UI controls is overcrowded on the screen. Complex menu hierarchy is also creating difficulties in accessing the right menu selection at the right time. The focus should be made in a clear and semantically consistent workflow of UIs and its controls [177]. Besides, user state management is an important aspect, remembering current user status and performing an activity in a particular sequence of actions an alarming concern [49].

5.4 Device incompatibility

Cross-device cooperation is an essential aspect of the distributed user interface. The interface elements, i.e., information or layouts should behave the same across multiple devices. In most cases, the final user interface is rendered unevenly on different dimensions, screen sizes and operating systems. In addition, certain applications required pre-installed libraries and utilities to perform a function or activate secondary activities. Support for cross-mobile/platform on the accessibility platform should be incorporated [222].

5.5 Context of use

A number of aspects pertain to the interaction between user, device and the environment are simulated, concurrently. The non-consideration of the context of use may result in deprived usability for smartphones. The device should intelligently adapt the context of use and manipulate the user interfaces accordingly. The context of use involves background noise, concurrent conversation and surrounding noise [223]. Environmental distraction such as noise has a serious effect on smartphone usability. Context-aware adaptation rules are not supported in all applications. Thus, the result of getting more precise and accurate information on device, environment and user profiles is overlooked [224].

5.6 Quick and easy identification of objects

Identification and selection of non-visual items on the screen is a challenging task. The logical order of non-visual items, contents and UI elements is a challenging opportunity. Quick and easy identification of non-visual items on the screen is a challenging activity for blind people. Identifying and locating a particular item on the touch screen and moving to the next portion of the screen or buttons is a challenging job, which is mainly due to the non-availability of physical controls on a smartphone.

5.7 Learnability and discoverability of the UIs

Learnability and discoverability is a critical challenge in currently available applications. Discoverability is the time factor and the degree of ease to which a user can begin into a productive interaction [225]. Earlier experience in operating an interface, the difficulty faced in the process of discovery and effective feedback in interacting with user interfaces are the contributing factors for effective learnability and usable experience.

5.8 Inadequate mapping of feedbacks with UIs

The first generation of haptic feedback is available in the form of vibratory motors, though still, this can provide a limited sensation to blind and visually impaired people [226]. Besides, it is difficult to understand the pattern of vibrations. In addition, the auditory feedback is prone to the noisy environment [227]. Haptic feedback and proper utilization of gestures are an issue. Consistent and appropriate feedback at the right place and the right time is inadequate [228].

5.9 Text entry, text manipulation and text selection

The typical keypad, inadequate labels, smaller UI elements and slow response of text-to-speech in text entry reduce efficiency. Some keypads have a single key responsible for punching multiple characters, which makes the typing speed slower. In addition, the QWERTY keypad is complicated to follow especially by pressing the nearby character such as M and I. The slow typing of keys is another issue for instance in the iOS system; the user has to wait for one second per key impression. The error rate and missed touch in using traditional keypads are responses recorded on touchscreen interfaces [229–231]. Due to the non-availability of physical keys on the soft keypad, the user tends to touch the wrong non-visual items. Moreover, there are many actions associated with one key, which creates confusion for these people. In the context of blind people, normally they are unaware of a specific type of functionality associated with a particular key.

5.9.1 Screen orientation, size and resolution

The primary factor that affects the usability of the touchscreen interface is screen elements, such as the size of the screen, orientation and control density [232]. It is evident that the small size of buttons and UI elements has a depriving effect on blind people in performing common activity on a smartphone. The larger size of non-visual components ensures a higher success ratio. Similarly, screen orientation also leads to an increase in the difficulty level of these people, as the user is familiar with one type of orientation (either portrait or landscape). Thus, the sudden change results in abnormal consequences. In addition, the button used for multiple purposes should be differentiated to avoid confusion.

6 Conclusion

We have reviewed research and innovation from the area of mobile/smartphone-based interventions for blind people with the aim to provide an outlook on how these technologies can play a role in supporting an improved quality of life. Smartphones provide a smart, portable, usable and interactive support to the blind people as compared to bulky, expensive and cumbersome assistive devices. Every blind or visually impaired person has their specific mobility, navigational, and orientational needs and capabilities to perform daily life activities [233]. It is essential to recognize individual capabilities to understand and accommodate the design and innovation process of any tech-based assistive aids. The user-centric design methodology describes the design process by meeting the end-user requirements and by judging their level of satisfaction [234]. Application designers are embracing this design paradigm by recognizing the diversity in the needs and capabilities of blind people as compared to sighted people. This design process is based on user-focused design tools and practices including interviews, focus groups, surveys and participatory design processes [235]. User-Centric Design (UCD) tools are critical to the success of assistive technologies for blind people. The user's opinion during the design process is the most critical success factor since the user in this area is more specialized. Interaction with these technologies should be made available in simple, memorable, easy to learn and consistent ways. Haptic feedback, gesture controls and eye-free technologies are upcoming interventions. Information architecture and the flow of navigational items should be organized in such a way so that cognitive load on the blind people should be kept a minimum as possible.

Haptic-based interactions can be used as a primary tool for improving user experience. Despite the extensive work carried out for blind people in the area of navigation, pathfinding, obstacle detection, access to information, user interactions, cognitive mapping, knowledge representation, etc., the challenges of collaborative data management, semantic representation of objects and point of interests, semantic query processing, reasoning & inferring, usable user interface, universal user interfaces and performance of graphical user interfaces of smartphones must be considered in devising new and innovative solutions for blind people. There is little evidence of direct interventions of a collaborative effort among medical experts and computer scientists for designing joint solutions for people with special needs.

We look at the issues and challenges of blind people in using smartphone-based assistive technologies. However, a number of challenging opportunities are cultivated for future research and development. These include: (1) the accessibility of large size touch screen devices such as tablets and large surface screen, (2) editing of Text, manipulation of non-visual item on the touchscreen interfaces, (3) usable text-entry mechanism, devising accessibility-inclusive and specialized keypad for blind people to improve the user experience, (4) understanding blind users' needs, expectations and their meaningful interpretation, (5) user interface distribution among wearable devices, smartwatches, smartphones and smart TVs, (6) universal user interfaces for performing common activities on smartphones, (7) incorporation of gesture-based system in interface design and the design of assistive solutions.

We strongly advocate the potential of smartphone-based technologies to be significantly enriched if computer scientists and medical experts work together to adopt a genuine design philosophy for the development of next-generation interfaces toward an improved quality of life for visually impaired and blind people.

References

1. Carterette, E.C.: Handbook of Perception, vol. 6A. Elsevier, Amsterdam (1978)
2. Binns, A.M., Bunce, C., Dickinson, C., Harper, R., Tudor-Edwards, R., Woodhouse, M., Linck, P., Suttie, A., Jackson, J., Lindsay, J.: How effective is low vision service provision? A systematic review. Surv. Ophthalmol. **57**(1), 34–65 (2012)
3. WHO: Visual Impairment and Blindness (2014). https://www.who.int/mediacentre/factsheets/fs282/en/
4. Manduchi, R., Coughlan, J.: (Computer) vision without sight. Commun. ACM **55**(1), 96–104 (2012)
5. Terven, J.R., Salas, J., Raducanu, B.: New opportunities for computer vision-based assistive technology systems for the visually impaired. Computer **47**(4), 52–58 (2014)
6. Kientz, J.A., Patel, S.N., Tyebkhan, A.Z., Gane, B., Wiley, J., Abowd, G.D.: Where's my stuff?: Design and evaluation of a mobile system for locating lost items for the visually impaired. In: Proceedings of the 8th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 103–110. ACM (2006)
7. Fruchterman, J.R.: In the palm of your hand: a vision of the future of technology for people with visual impairments. J. Vis. Impair. Blind **97**(10), 585–591 (2003)
8. McCarthy, J., Wright, P.: Technology as experience. Interactions **11**(5), 42–43 (2004)
9. Paek, T., Chickering, D.M.: Improving command and control speech recognition on mobile devices: using predictive user models for language modeling. User Model. User Adapt. Interact. **17**(1–2), 93–117 (2007)
10. Brewster, S.: Overcoming the lack of screen space on mobile computers. Pers. Ubiquitous Comput. **6**(3), 188–205 (2002)
11. Brewster, S., Chohan, F., Brown, L.: Tactile feedback for mobile interactions. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 159–162. ACM (2007)
12. Wall, S.A., Brewster, S.A.: Tac-tiles: multimodal pie charts for visually impaired users. In: Proceedings of the 4th Nordic Conference on Human–Computer Interaction: Changing Roles, pp. 9–18. ACM (2006)
13. Nicolau, H., Montague, K., Guerreiro, T., Rodrigues, A., Hanson, V.L.: HoliBraille: multipoint vibrotactile feedback on mobile devices. In: Proceedings of the 12th Web for All Conference, p. 30. ACM (2015)
14. Kuber, R., Hastings, A., Tretter, M., Fitzpatrick, D.: Determining the accessibility of mobile screen readers for blind users. In: Proceedings of IASTED HCI (2012)
15. Hakobyan, L., Lumsden, J., O'Sullivan, D., Bartlett, H.: Mobile assistive technologies for the visually impaired. Surv. Ophthalmol. **58**(6), 513–528 (2013)
16. Nah, F.F.-H., Zhang, D., Krogstie, J., Zhao, S.: Editorial of the Special Issue on Mobile Human–Computer Interaction. Taylor & Francis, New York (2017)
17. Damaceno, R.J.P., Braga, J.C., Mena-Chalco, J.P.: Mobile device accessibility for the visually impaired: problems mapping and recommendations. Univers. Access Inf. Soc. **17**, 421–435 (2018)
18. Guerreiro, T., Montague, K., Guerreiro, J., Nunes, R., Nicolau, H., Gonçalves, D.J.: Blind people interacting with large touch surfaces: strategies for one-handed and two-handed exploration. In: Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces, pp. 25–34. ACM (2015)
19. Oliveira, J., Guerreiro, T., Nicolau, H., Jorge, J., Gonçalves, D.: Blind people and mobile touch-based text-entry: acknowledging the need for different flavors. In: The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 179–186. ACM (2011)
20. Buzzi, M.C., Buzzi, M., Leporini, B., Trujillo, A.: Analyzing visually impaired people's touch gestures on smartphones. Multimed. Tools Appl. **76**, 5141–5169 (2017)
21. Southern, C., Clawson, J., Frey, B., Abowd, G., Romero, M.: Braille Touch: mobile touchscreen text entry for the visually impaired. In: Proceedings of the 14th International Conference on Human–Computer Interaction with Mobile Devices and Services Companion, pp. 155–156. ACM (2012)
22. Huang, H.: Blind users' expectations of touch interfaces: factors affecting interface accessibility of touchscreen-based smartphones for people with moderate visual impairment. Univers. Access Inf. Soc. **17**, 291–304 (2017)
23. Grussenmeyer, W., Folmer, E.: Accessible touchscreen technology for people with visual impairments: a survey. ACM Trans. Access. Comput: TACCESS **9**(2), 6 (2017)
24. Adipat, B., Zhang, D.: Interface design for mobile applications. AMCIS 2005 Proceedings, vol. 494 (2005)
25. Bhowmick, A., Hazarika, S.M.: An insight into assistive technology for the visually impaired and blind people: state-of-the-art and future trends. J. Multimodal User Interfaces **11**(2), 149–172 (2017)
26. Hu, M., Chen, Y., Zhai, G., Gao, Z., Fan, L.: An overview of assistive devices for blind and visually impaired people. Int. J. Robot. Autom. **34**(5), 580–598 (2019)
27. Darabont, D.C., Badea, D.O., Trifu, A., Fogarassy, P.: The impact of new assistive technologies on specific occupational risks for blind and visual impaired peoples. In: MATEC Web of Conferences, p. 00079. EDP Sciences (2020)
28. Abdolrahmani, A., Kuber, R., Hurst, A.: An empirical investigation of the situationally-induced impairments experienced

by blind mobile device users. In: Proceedings of the 13th Web for All Conference, pp. 1–8 (2016)
29. Bauer, S.M., Elsaesser, L.-J., Arthanat, S.: Assistive technology device classification based upon the World Health Organization's, International Classification of Functioning, Disability and Health (ICF). Disabil. Rehabil. Assist. Technol. **6**(3), 243–259 (2011)
30. Pal, J., Pradhan, M., Shah, M., Babu, R.: Assistive technology for vision-impairments: an agenda for the ICTD community. In: Proceedings of the 20th International Conference Companion on World Wide Web, pp. 513–522. ACM (2011)
31. Paiva, S., Gupta, N.: Technologies and systems to improve mobility of visually impaired people: a state of the art. In: Technological Trends in Improved Mobility of the Visually Impaired, pp. 105–123. Springer (2020)
32. Tapu, R., Mocanu, B., Tapu, E.: A survey on wearable devices used to assist the visual impaired user navigation in outdoor environments. In: 2014 11th International Symposium on Electronics and Telecommunications (ISETC), pp. 1–4. IEEE (2014)
33. Kim, H.K., Han, S.H., Park, J., Park, J.: The interaction experiences of visually impaired people with assistive technology: a case study of smartphones. Int. J. Ind. Ergon. **55**, 22–33 (2016)
34. Kane, S.K., Jayant, C., Wobbrock, J.O., Ladner, R.E.: Freedom to roam: a study of mobile device adoption and accessibility for people with visual and motor disabilities. In: Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 115–122. ACM (2009)
35. Madeley, R., Finnigan, J.: Facing blindness alone (2013)
36. Hersh, M., Johnson, M.A.: Assistive Technology for Visually Impaired and Blind People. Springer, Berlin (2010)
37. Brassai, S.T., Bako, L., Losonczi, L.: Assistive technologies for visually impaired people. Acta Univ. Sapientiae Electr. Mech. Eng. **3**, 39–50 (2011)
38. Brady, E., Morris, M.R., Zhong, Y., White, S., Bigham, J.P.: Visual challenges in the everyday lives of blind people. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 2117–2126. ACM (2013)
39. Csapó, Á., Wersényi, G., Nagy, H., Stockman, T.: A survey of assistive technologies and applications for blind users on mobile platforms: a review and foundation for research. J. Multimodal User Interfaces **9**(4), 275–286 (2015)
40. Taylor, B., Lee, D.-J., Zhang, D., Xiong, G.: Smart phone-based Indoor guidance system for the visually impaired. In: 2012 12th International Conference on Control Automation Robotics & Vision (ICARCV), pp. 871–876. IEEE (2012)
41. Behmer, J., Knox, S.: LocalEyes: accessible GPS and points of interest. In: Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 323–324. ACM (2010)
42. Billi, M., Burzagli, L., Catarci, T., Santucci, G., Bertini, E., Gabbanini, F., Palchetti, E.: A unified methodology for the evaluation of accessibility and usability of mobile applications. Univ. Access Inf. Soc. **9**(4), 337–356 (2010)
43. Szekely, P., Luo, P., Neches, R.: Beyond interface builders: model-based interface tools. In: Proceedings of the INTERACT'93 and CHI'93 Conference on Human Factors in Computing Systems, pp. 383–390. ACM (1993)
44. Alonso, F., Fuertes, J.L., González, Á.L., Martínez, L.: User-interface modelling for blind users. In: International Conference on Computers for Handicapped Persons, pp. 789–796. Springer (2008)
45. Abascal, J., Nicolle, C.: Moving towards inclusive design guidelines for socially and ethically aware HCI. Interact. Comput. **17**(5), 484–505 (2005)
46. Persad, U., Langdon, P., Clarkson, J.: Characterising user capabilities to support inclusive design evaluation. Univ. Access Inf. Soc. **6**(2), 119–135 (2007)
47. Plos, O., Buisine, S., Aoussat, A., Mantelet, F., Dumas, C.: A Universalist strategy for the design of Assistive technology. Int. J. Ind. Ergon. **42**(6), 533–541 (2012)
48. Long, S.K., Karpinsky, N.D., Döner, H., Still, J.D.: Using a mobile application to help visually impaired individuals explore the outdoors. In: Advances in Design for Inclusion, pp. 213–223. Springer, Cham (2016)
49. Kulyukin, V., Crandall, W., Coster, D.: Efficiency or quality of experience: a laboratory study of three eyes-free touchscreen menu browsing user interfaces for mobile phones. Open Rehabil. J. **4**, 13–22 (2011)
50. Khan, A., Khusro, S., Alam, I.: BlindSense—an accessibility-inclusive universal user interface for blind people. Eng. Technol. Appl. Sci. Res. **8**(2), 2775–2784 (2018)
51. Khan, A., Khusro, S.: Blind-friendly user interfaces–a pilot study on improving the accessibility of touchscreen interfaces. Multimed. Tools Appl. **78**(13), 17495–17519 (2019)
52. Khan, A., Khusro, S., Niazi, B., Ahmad, J., Alam, I., Khan, I.: TetraMail: a usable email client for blind people. Univ. Access Inf. Soc. **19**, 113–132 (2020). https://doi.org/10.1007/s10209-018-0633-5
53. Hink, R.B., Suarez, A.A.: Basic human computer interface for the blind. In: 8th Latin American and Caribbean conference for Engineering and Technology (LACCEI'2010), Arequipa, Peru (2010)
54. Bonner, M.N., Brudvik, J.T., Abowd, G.D., Edwards, W.K.: No-look notes: accessible eyes-free multi-touch text entry. In: International Conference on Pervasive Computing, pp. 409–426. Springer (2010)
55. McGookin, D., Brewster, S., Jiang, W.: Investigating touchscreen accessibility for people with visual impairments. In: Proceedings of the 5th Nordic Conference on Human–Computer Interaction: Building Bridges, pp. 298–307. ACM (2008)
56. Basori, A.H.: HapAR: handy intelligent multimodal haptic and audio-based mobile AR navigation for the visually impaired. In: Technological Trends in Improved Mobility of the Visually Impaired, pp. 319–334. Springer, Cham (2020)
57. Hill, D.R., Grieb, C.: Substitution for a restricted visual channel in multimodal computer–human dialogue. IEEE Trans. Syst. Man Cybern. **18**(2), 285–304 (1988)
58. Li, K.A., Baudisch, P., Hinckley, K.: Blindsight: eyes-free access to mobile phones. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 1389–1398. ACM (2008)
59. Kane, S.K., Bigham, J.P., Wobbrock, J.O.: Slide rule: making mobile touch screens accessible to blind people using multi-touch interaction techniques. In: Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 73–80. ACM (2008)
60. Chen, X., Tremaine, M., Lutz, R., Chung, J.-W., Lacsina, P.: AudioBrowser: a mobile browsable information access for the visually impaired. Univ. Access Inf. Soc. **5**(1), 4–22 (2006)
61. Guerreiro, T., Lagoá, P., Nicolau, H., Gonçalves, D., Jorge, J.A.: From tapping to touching: making touch screens accessible to blind users. IEEE Multimed. **15**(4), 0048–0050 (2008)
62. Brewster, S., Lumsden, J., Bell, M., Hall, M., Tasker, S.: Multimodal 'eyes-free' interaction techniques for wearable devices. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 473–480. ACM (2003)
63. Azenkot, S., Fortuna, E.: Improving public transit usability for blind and deaf-blind people by connecting a braille display to a smartphone. In: Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 317–318. ACM (2010)

64. Siqueira, J., de Melo Nunes, F.A.A., Ferreira, D.J., Silva, C.R.G., de Oliveira Berretta, L., Ferreira, C.B.R., Félix, I.M., da Silva Soares, A., da Costa, R.M., Luna, M.M.: Braille text entry on smartphones: A systematic review of the literature. In: 2016 IEEE 40th Annual Computer Software and Applications Conference (COMPSAC), Vol. 2, pp. 521–526. IEEE (2016).
65. Raman, T.V.: JustSpeak. https://eyes-free.blogspot.hu/ (2013)
66. vOICe. https://www.androlib.com/android.application.voice-voice-wiz.aspx (2016)
67. Dewhurst, D.: Creating and accessing audio-tactile images with "HFVE" vision substitution software. In: Proceedings of the Third Interactive Sonification Workshop. KTH, Stockholm, pp. 101–104 (2010)
68. Gomez-Valencia, J.D.: A Computer-Vision Based Sensory Substitution Device for the Visually Impaired (See ColOr). University of Geneva, Geneva (2014)
69. Inc, C.: TapTapSee - Blind & Visually Impaired Camera. https://www.taptapseeapp.com/ (2016)
70. Wilson, J., Walker, B.N., Lindsay, J., Cambias, C., Dellaert, F.: Swan: System for wearable audio navigation. In: 2007 11th IEEE International Symposium on Wearable Computers, pp. 91–98. IEEE (2007)
71. MIPsoft: BlindSquare. https://blindsquare.com/about/ (2016)
72. Stepnowski, A., Kamiński, Ł., Demkowicz, J.: Voice Maps—the system for navigation of blind in urban area. In: Proceedings of the 10th WSEAS International Conference on Applied Computer and Applied Computational Science, Venice, Italy (2011)
73. Khoshelham, K., Zlatanova, S.: Sensors for indoor mapping and navigation. Sensors **16**(5), 655 (2016)
74. Paredes, H., Fernandes, H., Martins, P., Barroso, J.: Gathering the users' needs in the development of assistive technology: a blind navigation system use case. In: International Conference on Universal Access in Human-Computer Interaction, pp. 79–88. Springer (2013)
75. Strumillo, P.: Electronic interfaces aiding the visually impaired in environmental access, mobility and navigation. In: 3rd International Conference on Human System Interaction, pp. 17–24. IEEE (2010)
76. Dakopoulos, D., Bourbakis, N.G.: Wearable obstacle avoidance electronic travel aids for blind: a survey. IEEE Trans. Syst. Man Cybern. Part C (Appl. Rev) **40**(1), 25–35 (2010)
77. Hussain, M.A., Ullah, M.G., Fareed, A., Sohail, B.: The smartcane for blind people an electronically smart stick to aid mobility. Int. J. Comput. Sci. Inf. Secur. **14**(4), 276 (2016)
78. Vigo, M., Brajnik, G.: Automatic web accessibility metrics: where we are and where we can go. Interact. Comput. **23**(2), 137–155 (2011)
79. Garaj, V., Jirawimut, R., Ptasinski, P., Cecelja, F., Balachandran, W.: A system for remote sighted guidance of visually impaired pedestrians. Br. J. Visu. Impair. **21**(2), 55–63 (2003)
80. Doush, I.A., Alshatnawi, S., Al-Tamimi, A.-K., Alhasan, B., Hamasha, S.: ISAB: integrated indoor navigation system for the blind. Interact. Comput. **29**, 181–202 (2016)
81. Magatani, K., Sawa, K., Yanashima, K.: Development of the navigation system for the visually impaired by using optical beacons. In: Proceedings of the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2001, pp. 1488–1490. IEEE (2001)
82. Bowen III, C.L., Buennemeyer, T.K., Burbey, I., Joshi, V.: Using wireless networks to assist navigation for individuals with disabilities. In: California State University, Northridge Center on Disabilities' 21st Annual International Technology and Persons with Disabilities Conference (2006)
83. Shiizu, Y., Hirahara, Y., Yanashima, K., Magatani, K.: The development of a white cane which navigates the visually impaired. In: Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE 2007, pp. 5005–5008. IEEE
84. Miller, L.E.: Indoor Navigation for First responders: A Feasibility Study. Princeton, Citeseer (2006)
85. Magrassi, P., Berg, T.: A world of smart objects: the role of auto identification technologies. Strategic Analysis Report, Gartner (2001)
86. Meints, M.: D3. 7 a structured collection on information and literature on technological and usability aspects of radio frequency identification (rfid). FIDIS Deliv. **3**(7) (2007)
87. Amemiya, T., Yamashita, J., Hirota, K., Hirose, M.: Virtual leading blocks for the deaf-blind: a real-time way-finder by verbal-nonverbal hybrid interface and high-density RFID tag space. In: Proceedings of IEEE Virtual Reality, 2004, pp. 165–287. IEEE (2004)
88. Lawson, M.A., Do, E.Y.-L., Marston, J.R., Ross, D.A.: Helping hands versus ERSP vision: comparing object recognition technologies for the visually impaired. In: HCI International 2011-Posters' Extended Abstracts, pp. 383–388. Springer (2011)
89. Biader Ceipidor, U., Medaglia, C.M., Serbanati, A., Azzalin, G., Barboni, M., Rizzo, F., Sironi, M.: SeSaMoNet: an RFID-based economically viable navigation system for the visually impaired. Int. J. RF Technol. Res. Appl. **1**(3), 214–224 (2009)
90. Seto, T., Magatani, K.: A navigation system for the visually impaired using colored navigation lines and RFID tags. In: Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2009. EMBC 2009, pp. 831–834. IEEE (2009)
91. Kiers, M., Sovec, T.: Ways4all: indoor navigation for visually impaired and blind people (2010)
92. Vogel, C., Fay, A., König, A., Cory, D., Usadel, J.: BUS-ID: Barrierefreier Zugang blinder und sehbehinderter Menschen zum öffentlichen Nahverkehr durch Einsatz von RFID. In: 13th International Mobility Conference, Marburg, p. 17 (2009)
93. Chumkamon, S., Tuvaphanthaphiphat, P., Keeratiwintakorn, P.: A blind navigation system using RFID for indoor environments. In: 5th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, 2008. ECTI-CON 2008, pp. 765–768. IEEE (2008)
94. Di Giampaolo, E.: A passive-RFID based indoor navigation system for visually impaired people. In: 2010 3rd International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL), pp. 1–5. IEEE (2010)
95. Kassim, A., Yasuno, T., Suzuki, H., Jaafar, H., Aras, M.: Indoor navigation system based on passive RFID transponder with digital compass for visually impaired people. Int. J. Adv. Comput. Sci. Appl. **7**(2), 604–611 (2016)
96. Tandon, K., Pande, T., Adil, M., Dubey, G., Kumar, A.: A blind navigation system using RFID for indoor environments. Int. J. Comput. Syst. **2**(4), 115–118 (2015)
97. Doush, I.A., Damaj, I., Al-Betar, M.A., Awadallah, M.A., Ra'ed, M., Alchalabi, A.E., Bolaji, A.L.: A Survey on accessible context-aware systems. In: Technological Trends in Improved Mobility of the Visually Impaired, pp. 29–63. Springer (2020)
98. Kandil, M., AlAttar, F., Al-Baghdadi, R., Damaj, I.: AmIE: An ambient intelligent environment for blind and visually impaired people. In: Technological Trends in Improved Mobility of the Visually Impaired, pp. 207–236. Springer, Cham (2020)
99. Ding, B., Yuan, H., Jiang, L., Zang, X.: The research on blind navigation system based on RFID. In: 2007 International Conference on Wireless Communications, Networking and Mobile Computing, pp. 2058–2061. IEEE (2007)
100. Willis, S., Helal, S.: RFID information grid for blind navigation and wayfinding. In: Ninth IEEE International Symposium on Wearable Computers (ISWC'05), pp. 34–37. IEEE (2005)
101. Sivan, S., Darsan, G.: Computer vision based assistive technology for blind and visually impaired people. In: Proceedings of

the 7th International Conference on Computing Communication and Networking Technologies, p. 41. ACM (2016)
102. Jafri, R., Ali, S.A., Arabnia, H.R., Fatima, S.: Computer vision-based object recognition for the visually impaired in an indoors environment: a survey. Vis. Comput. **30**(11), 1197–1222 (2014)
103. Jafri, R., Ali, S.A., Arabnia, H.R.: Face recognition for the visually impaired. In: Proceedings of the International Conference on Information and Knowledge Engineering (IKE), p. 1. The Steering Committee of The World Congress in Computer Science, Computer Engineering and Applied Computing (WorldComp) (2013)
104. McGowan, T.: Object Recognition for the Visually Impaired. Dublin City University, Dublin (1997)
105. Dumitras, T., Lee, M., Quinones, P., Smailagic, A., Siewiorek, D., Narasimhan, P.: Eye of the beholder: phone-based text-recognition for the visually-impaired. In: 2006 10th IEEE International Symposium on Wearable Computers, pp. 145–146. IEEE (2006)
106. Al-Khalifa, H.S.: Utilizing QR Code and Mobile Phones for Blinds and Visually Impaired People. Springer, Berlin (2008)
107. Chang, Y.-J., Tsai, S.-K., Wang, T.-Y.: A context aware handheld wayfinding system for individuals with cognitive impairments. In: Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 27–34. ACM (2008)
108. Chang, Y.-J., Tsai, S.-K., Chang, Y.-S., Wang, T.-Y.: A novel wayfinding system based on geo-coded QR codes for individuals with cognitive impairments. In: Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 231–232. ACM (2007)
109. Jafri, R., Ali, S.A., Arabnia, H.R.: Computer vision-based object recognition for the visually impaired using visual tags. In: The 2013 International Conference on Image Processing, Computer Vision, and Pattern Recognition, pp. 400–406 (2013)
110. Nagarajan, R., Yaacob, S., Sainarayanan, G.: Role of object identification in sonification system for visually impaired. In: TENCON 2003. Conference on Convergent Technologies for the Asia-Pacific Region, pp. 735–739. IEEE (2003)
111. Iannizzotto, G., Costanzo, C., Lanzafame, P., La Rosa, F.: Badge3D for visually impaired. In: 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05)-Workshops, pp. 29–29. IEEE (2005)
112. Gude, R., Østerby, M., Soltveit, S.: Blind navigation and object recognition. Laboratory for Computational Stochastics, University of Aarhus, Denmark (2008)
113. Al-Khalifa, H.S.: Utilizing QR code and mobile phones for blinds and visually impaired people. In: International Conference on Computers for Handicapped Persons, pp. 1065–1069. Springer (2008)
114. Zöllner, M., Huber, S., Jetter, H.-C., Reiterer, H.: NAVI—a proof-of-concept of a mobile navigational aid for visually impaired based on the microsoft kinect. In: IFIP Conference on Human–Computer Interaction, pp. 584–587. Springer (2011)
115. Sudol, J., Dialameh, O., Blanchard, C., Dorcey, T.: Looktel—a comprehensive platform for computer-aided visual assistance. In: 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition-Workshops, pp. 73–80. IEEE (2010)
116. Islam, M.T., Ahmad, M., Bappy, A.S.: Microprocessor-based smart blind glass system for visually impaired people. In: Proceedings of International Joint Conference on Computational Intelligence, pp. 151–161. Springer (2020)
117. Cunneen, M., Mullins, M., Murphy, F., Shannon, D., Furxhi, I., Ryan, C.: Autonomous vehicles and avoiding the trolley (dilemma): vehicle perception, classification, and the challenges of framing decision ethics. Cybern. Syst. **51**(1), 59–80 (2020)
118. Silva, S., Almeida, N., Pereira, C., Martins, A.I., Rosa, A.F., e Silva, M.O., Teixeira, A.: Design and development of multimodal applications: a vision on key issues and methods. In: International Conference on Universal Access in Human–Computer Interaction, pp. 109–120. Springer (2015)
119. Konttila, A., Harjumaa, M., Muuraiskangas, S., Jokela, M., Isomursu, M.: Touch n'Tag: digital annotation of physical objects with voice tagging. J. Assist. Technol. **6**(1), 24–37 (2012)
120. Kulyukin, V., Kutiyanawala, A.: From ShopTalk to ShopMobile: vision-based barcode scanning with mobile phones for independent blind grocery shopping. In: Proceedings of the 2010 Rehabilitation Engineering and Assistive Technology Society of North America Conference (RESNA 2010), Las Vegas, NV (2010)
121. Ran, L., Helal, S., Moore, S.: Drishti: an integrated indoor/outdoor blind navigation system and service. In: Proceedings of the Second IEEE Annual Conference on Pervasive Computing and Communications, 2004. PerCom 2004, pp. 23–30. IEEE (2004)
122. Martinez-Sala, A.S., Losilla, F., Sánchez-Aarnoutse, J.C., García-Haro, J.: Design, implementation and evaluation of an indoor navigation system for visually impaired people. Sensors **15**(12), 32168–32187 (2015)
123. Ali, S., Khusro, S.: Mobile Phone Sensing: A New Application Paradigm. Indian J. Sci. Technol. **9**(19), 1–42 (2016)
124. Zelek, J.: The E.(Ben) & Mary Hochhausen Fund for Research in Adaptive Technology For Blind and Visually Impaired Persons (2002)
125. Golding, A.R., Lesh, N.: Indoor navigation using a diverse set of cheap, wearable sensors. In: The Third International Symposium on Wearable Computers, 1999. Digest of Papers, pp. 29–36. IEEE (1999)
126. Sánchez, J., de la Torre, N.: Autonomous navigation through the city for the blind. In: Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 195–202. ACM (2010)
127. Bahl, P., Padmanabhan, V.N.: RADAR: An in-building RF-based user location and tracking system. In: Proceedings IEEE INFOCOM 2000. Conference on Computer Communications. Nineteenth Annual Joint Conference of the IEEE Computer and Communications Societies (Cat. No. 00CH37064), Vol. 2, pp. 775–784. IEEE (2000)
128. Denham, J., Leventhal, J., McComas, H.: Getting from point A to point B: a review of two GPS systems. (2004)
129. Collins, C.C.: On mobility aids for the blind. In: Electronic Spatial Sensing for the Blind, pp. 35–64. Springer, Berlin (1985)
130. Google: Intersection Explorer. https://play.google.com/store/apps/details?id=com.google.android.marvin.intersectionexplorer&hl=en (2016)
131. Hub, A., Kombrink, S., Bosse, K., Ertl, T.: TANIA—a tactile-acoustical navigation and information assistant for the 2007 CSUN conference. In: Conference Proceedings of the California State University, Northridge Center on Disabilities' 22nd Annual International Technology and Persons with Disabilities Conference, March 19–24, Los Angeles, CA, USA (2007)
132. Antunes, A.C., Silva, C.: Designing for blind users: guidelines for developing mobile apps for supporting navigation of blind people on public transports. In: User-Centered Software Development for the Blind and Visually Impaired: Emerging Research and Opportunities, pp. 1–25. IGI Global (2020)
133. Ali, S., Khusro, S., Ullah, I., Khan, A., Khan, I.: SmartOntoSensor: ontology for semantic interpretation of smartphone sensors data for context-aware applications. J. Sens. **2017** (2017)
134. Faugeras, O.D., Hebert, M.: The representation, recognition, and locating of 3-D objects. Int. J. Robot. Res. **5**(3), 27–52 (1986)
135. Kay, L.: Auditory perception of objects by blind persons, using a bioacoustic high resolution air sonar. J. Acoust. Soc. Am. **107**(6), 3266–3275 (2000)

136. Meijer, P.B.: An experimental system for auditory image representations. IEEE Trans. Biomed. Eng. **39**(2), 112–121 (1992)
137. Laursen, L.: Echolocation Via Smartphone. https://spectrum.ieee.org/consumer-electronics/portable-devices/echolocation-by-smartphone-possible (2015)
138. Schwartz, M., Benkert, D.: Navigating with a visual impairment: problems, tools and possible solutions. In: International Conference on Augmented Cognition, pp. 371–381. Springer (2016)
139. Hill, J., Black, J.: The miniguide: a new electronic travel device. J. Vis. Impair. Blind. **97**(10), 1–6 (2003)
140. Hoyle, B., & Waters, D.: Mobility at: The batcane (ultracane). In: Assistive Technology for Visually Impaired and Blind People, pp. 209–229. Springer, London (2008)
141. Shoval, S., Ulrich, I., Borenstein, J.: NavBelt and the Guide-Cane [obstacle-avoidance systems for the blind and visually impaired]. IEEE Robot. Autom. Mag. **10**(1), 9–20 (2003)
142. Gammeter, S., Gassmann, A., Bossard, L., Quack, T., Van Gool, L.: Server-side object recognition and client-side object tracking for mobile augmented reality. In: 2010 IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), pp. 1–8. IEEE (2010)
143. Khan, A., Khusro, S., Rauf, A., Mahfooz, S.: Rebirth of augmented reality-enhancing reality via smartphones. Bahria Univ. J. Inf. Commun. Technol. **8**(1), 110 (2015)
144. Khan, A., Khusro, S.: The rise of augmented reality browsers: trends, challenges and opportunities (Review paper). Pak. J. Sci. **67**(3), 288–300 (2015)
145. Blum, J.R., Bouchard, M., Cooperstock, J.R.: What's around me? Spatialized audio augmented reality for blind users with a smartphone. In: Mobile and Ubiquitous Systems: Computing, Networking, and Services, pp. 49–62. Springer (2012)
146. Loomis, J.M., Golledge, R.G., Klatzky, R.L., Speigle, J.M., Tietz, J.: Personal guidance system for the visually impaired. In: Proceedings of the First Annual ACM Conference on Assistive Technologies, pp. 85–91. ACM (1994)
147. Golledge, R.G., Loomis, J.M., Klatzky, R.L., Flury, A., Yang, X.L.: Designing a personal guidance system to aid navigation without sight: progress on the GIS component. Int. J. Geogr. Inf. Syst. **5**(4), 373–395 (1991)
148. Petrie, H., Johnson, V., Strothotte, T., Raab, A., Fritz, S., Michel, R.: MoBIC: designing a travel aid for blind and elderly people. J. Navig. **49**(01), 45–52 (1996)
149. Lorenz, B., Ohlbach, H.J., Stoffel, E.-P.: A hybrid spatial model for representing indoor environments. In: International Symposium on Web and Wireless Geographical Information Systems, pp. 102–112. Springer (2006)
150. D'Atri, E., Medaglia, C.M., Serbanati, A., Ceipidor, U.B.: A system to aid blind people in the mobility: a usability test and its results. In: Second International Conference on Systems, 2007. ICONS'07, pp. 35–35. IEEE (2007)
151. Jacobson, R.D.: Cognitive mapping without sight: four preliminary studies of spatial learning. J. Environ. Psychol. **18**(3), 289–305 (1998)
152. Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, B.: Recent advances in augmented reality. IEEE Comput. Graph. Appl. **21**(6), 34–47 (2001)
153. Passini, R., Proulx, G.: Wayfinding without vision an experiment with congenitally totally blind people. Environ. Behav. **20**(2), 227–252 (1988)
154. Lahav, O., Mioduser, D.: Haptic-feedback support for cognitive mapping of unknown spaces by people who are blind. Int. J. Hum Comput Stud. **66**(1), 23–35 (2008)
155. Crandall, W., Bentzen, B., Myers, L., Mitchell, P.: Transit accessibility improvement through talking signs remote infrared signage. A demonstration and evaluation (1995)
156. Shaik, A.S., Hossain, G., Yeasin, M.: Design, development and performance evaluation of reconfigured mobile Android phone for people who are blind or visually impaired. In: Proceedings of the 28th ACM International Conference on Design of Communication, pp. 159–166. ACM (2010)
157. Yatani, K., Banovic, N., Truong, K.: SpaceSense: representing geographical information to visually impaired people using spatial tactile feedback. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 415–424. ACM (2012)
158. Marston, J.R., Loomis, J.M., Klatzky, R.L., Golledge, R.G., Smith, E.L.: Evaluation of spatial displays for navigation without sight. ACM Trans. Appl. Percept.: TAP **3**(2), 110–124 (2006)
159. Parkes, D.: NOMAD": an audio-tactile tool for the acquisition, use and management of spatially distributed information by partially sighted and blind persons. In: Proceedings of Second International Conference on Maps and Graphics for Visually Disabled People, pp. 24–29 (1989)
160. Tsetsos, V., Anagnostopoulos, C., Kikiras, P., Hadjiefthymiades, S.: Semantically enriched navigation for indoor environments. Int. J. Web Grid Serv. **2**(4), 453–478 (2006)
161. Joseph, S.L., Zhang, X., Dryanovski, I., Xiao, J., Yi, C., Tian, Y.: Semantic indoor navigation with a blind-user oriented augmented reality. In: 2013 IEEE International Conference on Systems, Man, and Cybernetics, pp. 3585–3591. IEEE (2013)
162. Karimi, H.A.: Universal navigation. In: Universal Navigation on Smartphones, pp. 75–88. Springer, Boston, MA (2011)
163. Lorenz, B., Ohlbach, H.J., Stoffel, E.-P.: A hybrid spatial model for representing indoor environments. In: Web and Wireless Geographical Information Systems, pp. 102–112. Springer, Berlin (2006)
164. Horrocks, I.: Ontologies and the semantic web. Commun. ACM **51**(12), 58–67 (2008)
165. Camossi, E., Villa, P., Mazzola, L.: Semantic-based anomalous pattern discovery in moving object trajectories. arXiv:1305.1946 (2013)
166. Parent, C., Spaccapietra, S., Renso, C., Andrienko, G., Andrienko, N., Bogorny, V., Damiani, M.L., Gkoulalas-Divanis, A., Macedo, J., Pelekis, N.: Semantic trajectories modeling and analysis. ACM Comput. Surv. (CSUR) **45**(4), 42 (2013)
167. Yan, Z., Chakraborty, D., Parent, C., Spaccapietra, S., Aberer, K.: SeMiTri: a framework for semantic annotation of heterogeneous trajectories. In: Proceedings of the 14th international Conference on Extending Database Technology, pp. 259–270. ACM (2011)
168. José, J., Farrajota, M., Rodrigues, J.M.: Du Buf, J.H.: The SmartVision local navigation aid for blind and visually impaired persons. JDCTA **5**(5), 362–375 (2011)
169. Calder, D.J.: Ecological solutions for the blind. In: 4th IEEE International Conference on Digital Ecosystems and Technologies, pp. 625–630. IEEE (2010)
170. Zhang, J., Lip, C.W., Ong, S.-K., Nee, A.Y.: A multiple sensor-based shoe-mounted user interface designed for navigation systems for the visually impaired. In: 2010 The 5th Annual ICST Wireless Internet Conference (WICON), pp. 1–8. IEEE (2010)
171. Peng, E., Peursum, P., Li, L., Venkatesh, S.: A smartphone-based obstacle sensor for the visually impaired. In: Ubiquitous Intelligence and Computing, pp. 590–604. Springer, Berlin (2010)
172. Amemiya, T., Sugiyama, H.: Haptic handheld wayfinder with pseudo-attraction force for pedestrians with visual impairments. In: Proceedings of the 11th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 107–114. ACM (2009)
173. Amemiya, T.: Haptic direction indicator for visually impaired people based on pseudo-attraction force. Minds Int. J. Hum. Comput. Interact. **1**(5), 23–34 (2009)

174. Velázquez, R., Maingreaud, F., Pissaloux, E.: Intelligent glasses: a new man-machine interface concept integrating computer vision and human tactile perception. In: Proceedings of EuroHaptics, pp. 456–460. Citeseer (2003)
175. Joseph, S.L., Zhang, X., Dryanovski, I., Xiao, J., Yi, C., Tian, Y.: Semantic indoor navigation with a blind-user oriented augmented reality. In: 2013 IEEE International Conference on Systems, Man, and Cybernetics, pp. 3585–3591. IEEE (2013)
176. Schmetzke, A.: Web accessibility at university libraries and library schools. Libr. Hi Tech **19**(1), 35–49 (2001)
177. Leporini, B., Buzzi, M.C., Buzzi, M.: Interacting with mobile devices via VoiceOver: usability and accessibility issues. In: Proceedings of the 24th Australian Computer–Human Interaction Conference, pp. 339–348. ACM (2012)
178. Kane, S.K., Wobbrock, J.O., Ladner, R.E.: Usable gestures for blind people: understanding preference and performance. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 413–422. ACM (2011)
179. Rodrigues, A., Montague, K., Nicolau, H., Guerreiro, T.: Getting smartphones to TalkBack: understanding the smartphone adoption process of blind users. In: Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility, pp. 23–32. ACM (2015)
180. Borodin, Y., Mahmud, J., Ramakrishnan, I.V., Stent, A.: The HearSay non-visual web browser. In: Proceedings of the 2007 International Cross-Disciplinary Conference on Web Accessibility (W4A), pp. 128–129. ACM (2007)
181. Borodin, Y., Dausch, G., Ramakrishnan, I.V.: TeleWeb: accessible service for web browsing via phone. In: Proceedings of the 2009 International Cross-Disciplinary Conference on Web Accessibililty (W4A), pp. 96–97. ACM (2009)
182. Chu, C.N.: Two dimension interactive voice browser for the visually impaired. In: International Conference on Computers for Handicapped Persons, pp. 721–724. Springer, Berlin, Heidelberg (2004)
183. Ghose, R., Dasgupta, T., Basu, A.: Architecture of a web browser for visually handicapped people. In: Students' Technology Symposium (TechSym), IEEE, pp. 325–329. IEEE (2010)
184. Krajnc, E., Knoll, M., Feiner, J., Traar, M.: A touch sensitive user interface approach on smartphones for visually impaired and blind persons. In: Information Quality in e-Health. pp. 585–594. Springer, Berlin (2011)
185. Preece, A.: An Evaluation of the RAY G300, an Android-based Smartphone Designed for the Blind and Visually Impaired (2013)
186. Yong, R.: "VisionTouch Phone" for the blind. Malays. J. Med. Sci. **20**(5), 1–4 (2013)
187. Mascetti, S., Bernareggi, C., Belotti, M.: TypeInBraille: a braille-based typing application for touchscreen devices. In: The Proceedings of the 13th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 295–296 (2011)
188. Jayant, C., Acuario, C., Johnson, W., Hollier, J., Ladner, R.: V-braille: haptic braille perception using a touch-screen and vibration on mobile phones. In: Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 295–296. ACM (2010)
189. Bonner, M.N., Brudvik, J.T., Abowd, G.D., Edwards, W.K.: No-look notes: accessible eyes-free multi-touch text entry. In: Pervasive Computing, pp. 409–426. Springer, Berlin (2010)
190. Pirhonen, A., Brewster, S., Holguin, C.: Gestural and audio metaphors as a means of control for mobile devices. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 291–298. ACM (2002)
191. Frey, B., Southern, C., Romero, M.: Brailletouch: mobile texting for the visually impaired. In: Universal Access in Human–Computer Interaction. Context Diversity, pp. 19–25. Springer, Berlin (2011)
192. Nesbat, S.B.: A system for fast, full-text entry for small electronic devices. In: Proceedings of the 5th International Conference on Multimodal Interfaces, pp. 4–11. ACM (2003)
193. Dasgupta, T., Anuj, A., Sinha, M., Ghose, R., Basu, A.: VoiceMail architecture in desktop and mobile devices for the Blind people. In: 2012 4th International Conference on Intelligent Human Computer Interaction (IHCI), pp. 1–6. IEEE (2012)
194. Basu, A., Roy, S., Dutta, P., Banerjee, S.: A PC based multiuser Braille reading system for the blind libraries||. IEEE Trans. Rehabil. Eng. **6**(1), 60–68 (1998)
195. Blenkhorn, P.: A system for converting Braille into print. IEEE Trans. Rehabil. Eng. **3**(2), 215–221 (1995)
196. Blomquist, M., Burman, P.: The WinBraille approach to producing braille quickly and effectively. In: Computers Helping People with Special Needs, pp. 618–619. Springer, Berlin (2002)
197. www.brailler.com., b.R.f.
198. Dasgupta, T., Basu, A.: A speech enabled Indian language text to Braille transliteration system. In: 2009 International Conference on Information and Communication Technologies and Development (ICTD), pp. 201–211. IEEE (2009)
199. Kalra, N., Lauwers, T., Dewey, D., Stepleton, T., Dias, M.B.: Iterative design of a Braille writing tutor to combat illiteracy. In: ICTD 2007. International Conference on Information and Communication Technologies and Development, 2007, pp. 1–9. IEEE (2007)
200. Lahiri, A., Chattopadhyay, S.J., Basu, A.: Sparsha: A comprehensive Indian language toolset for the blind. In: Proceedings of the 7th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 114–120. ACM (2005)
201. Lee, K.-F., Hon, H.-W., Reddy, R.: An overview of the SPHINX speech recognition system. IEEE Trans. Acoust. Speech Signal Process. **38**(1), 35–45 (1990)
202. Linghao, Z., Ying, L.: On methods of designing smartphone interface. In: 2010 IEEE International Conference on Software Engineering and Service Sciences (ICSESS), pp. 584–587. IEEE (2010)
203. González, M., Moreno, L., Martínez, P.: Approach design of an accessible media player. Univ. Access Inf. Soc. **14**(1), 45–55 (2015)
204. Klingenberg, O.G., Holkesvik, A.H., Augestad, L.B.: Digital learning in mathematics for students with severe visual impairment: a systematic review. Br. J. Vis. Impair. **38**, 38–57 (2020)
205. Armano, T., Capietto, A., Illengo, M., Murru, N., Rossini, R.: An overview on ICT for the accessibility of scientific texts by visually impaired students. In: Congresso Nazionale SIREM 2014, pp. 119–122. Sie-L Editore (2015)
206. Cervone, D.: MathJax: a platform for mathematics on the Web. Not. AMS **59**(2), 312–316 (2012)
207. Federico, M., Furini, M.: Enhancing learning accessibility through fully automatic captioning. In: Proceedings of the International cross-Disciplinary Conference on Web Accessibility, pp. 1–4 (2012)
208. Wald, M.: Crowdsourcing correction of speech recognition captioning errors. In: Proceedings of the International Cross-Disciplinary Conference on Web Accessibility, pp. 1–2 (2011)
209. Encelle, B., Beldame, M.O., Prié, Y.: Towards the usage of pauses in audio-described videos. In: Proceedings of the 10th International Cross-Disciplinary Conference on Web Accessibility, pp. 1–4 (2013)
210. Wu, M., Balakrishnan, R.: Multi-finger and whole hand gestural interaction techniques for multi-user tabletop displays. In: Proceedings of the 16th Annual ACM Symposium on User Interface Software and Technology, pp. 193–202. ACM (2003)

211. Stephanidis, C., Savidis, A.: Interface development toolkits for non-visual and switch-based interaction. In: Proceedings of ERCIM News, Special Theme. Human Computer Interaction, vol. 46, pp. 4–15 (2001)
212. Romero, M., Frey, B., Southern, C., Abowd, G.D.: BrailleTouch: designing a mobile eyes-free soft keyboard. In: Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services, pp. 707–709. ACM (2011)
213. Buxton, W., Hill, R., Rowley, P.: Issues and techniques in touch-sensitive tablet input. ACM SIGGRAPH Comput. Graph. **19**(3), 215–224 (1985)
214. Shneiderman, B.: Designing the User Interface-Strategies for Effective Human–Computer Interaction. Pearson Education India, Bangalore (1986)
215. Bigham, J.P., Cavender, A.C., Brudvik, J.T., Wobbrock, J.O., Lander, R.E.: WebinSitu: a comparative analysis of blind and sighted browsing behavior. In: Proceedings of the 9th International ACM SIGACCESS Conference on Computers and Accessibility, pp. 51–58. ACM (2007)
216. Lazar, J., Allen, A., Kleinman, J., Malarkey, C.: What frustrates screen reader users on the web: a study of 100 blind users. Int. J. Hum. Comput. Interact. **22**(3), 247–269 (2007)
217. Vatavu, R.-D.: Visual impairments and mobile touchscreen interaction: state-of-the-art, causes of visual impairment, and design guidelines. Int. J. Hum. Comput. Interact. **33**(6), 486–509 (2017)
218. Lang, T.: Comparing website accessibility evaluation methods and learnings from usability evaluation methods. Peak usability (2003)
219. Nielsen, C.M., Overgaard, M., Pedersen, M.B., Stage, J., Stenild, S.: It's worth the hassle!: the added value of evaluating the usability of mobile systems in the field. In: Proceedings of the 4th Nordic Conference on Human–Computer Interaction: Changing Roles, pp. 272–280. ACM (2006)
220. Viana, W., Andrade, R.M.: XMobile: a MB-UID environment for semi-automatic generation of adaptive applications for mobile devices. J. Syst. Softw. **81**(3), 382–394 (2008)
221. Inostroza, R., Rusu, C., Roncagliolo, S., Jimenez, C., Rusu, V.: Usability heuristics for touchscreen-based mobile devices. In: 2012 Ninth International Conference on Information Technology: New Generations (ITNG), pp. 662–667. IEEE (2012)
222. Meskens, J., Vermeulen, J., Luyten, K., Coninx, K.: Gummy for multi-platform user interface designs: shape me, multiply me, fix me, use me. In: Proceedings of the Working Conference on Advanced Visual Interfaces, pp. 233–240. ACM (2008)
223. Tsiaousis, A.S., Giaglis, G.M.: An empirical assessment of environmental factors that influence the usability of a mobile website. In: 2010 Ninth International Conference on 2010 Mobile Business and 2010 Ninth Global Mobility Roundtable (ICMB-GMR), pp. 161–167. IEEE
224. Seffah, A., Javahery, H.: Multiple User Interfaces: Multi-Devices, Cross-Platform and Context-Awareness. Wiley, Hoboken (2003)
225. Chen, F.: Designing Human Interface in Speech Technology. Springer, Berlin (2006)
226. Alur, A., Shrivastav, P., Jumde, A.: Haptic technology: a comprehensive review of its applications and future prospects. Int. J. Comput. Sci. Inf. Technol.: IJCSIT **5**(5), 6039–6043 (2014)
227. Buzzi, M.C., Buzzi, M., Leporini, B., Paratore, M.T.: Vibro-tactile enrichment improves blind user interaction with mobile touchscreens. In: IFIP Conference on Human–Computer Interaction, pp. 641–648. Springer (2013)
228. Hatwell, Y., Streri, A., Gentaz, E.: Touching for Knowing: Cognitive Psychology of Haptic Manual Perception, vol. 53. John Benjamins Publishing, Amsterdam (2003)
229. Park, K., Goh, T., So, H.-J.: Toward accessible mobile application design: developing mobile application accessibility guidelines for people with visual impairment. In: Proceedings of HCI Korea 2014, pp. 31–38. Hanbit Media, Inc.
230. Dim, N.K., Ren, X.: Designing motion gesture interfaces in mobile phones for blind people. J. Comput. Sci. Technol. **29**(5), 812–824 (2014)
231. Façanha, A.R., Viana, W., Pequeno, M.C., de Borba Campos, M., Sánchez, J.: Touchscreen mobile phones virtual keyboarding for people with visual disabilities. In: International Conference on Human–Computer Interaction, pp. 134–145. Springer (2014)
232. Chiti, S., Leporini, B.: Accessibility of android-based mobile devices: a prototype to investigate interaction with blind users. In: Computers Helping People with Special Needs, pp. 607–614 (2012)
233. Strumillo, P.: Electronic interfaces aiding the visually impaired in environmental access, mobility and navigation. In: 2010 3rd Conference on Human System Interactions (HSI), pp. 17–24. IEEE (2010)
234. Abras, C., Maloney-Krichmar, D., Preece, J.: User-centered design. In: Bainbridge, W. (ed.) Encyclopedia of Human–Computer Interaction, vol. 37, no. 4, pp. 445–456. Sage, Thousand Oaks (2004)
235. Cober, R., Au, O., Son, J.J.: Using a participatory approach to design a technology-enhanced museum tour for visitors who are blind. In: Proceedings of the 2012 iConference, pp. 592–594. ACM (2012)