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Design of Navigation Applications for People with Disabilities: A Review of Literature and Guideline Formulation

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ABSTRACT

A mobile navigation application (App) can provide flexible wayfinding guidance, save time, and reduce stress for people in unfamiliar buildings or environments. Wayfinding is also a challenging task for individuals with disabilities. The objective of this study was to provide a comprehensive set of guidelines for designing navigation apps for individuals with disabilities. A review of the literature was conducted on scientific studies and commercially available navigation apps using Web of Science, Compendex, ACM Digital Library, IEEE Xplore, Wiley Online, Science Direct, SpringerLink, Taylor & Francis, Apple store, and Google Play. The findings led to 82 design guidelines categorized based on Nielsen's usability principles. The guidelines were implemented in an interface prototype to help users navigate places within a shopping mall. The prototype demonstrated that the proposed design guidelines are easily applicable and provided a roadmap for the future design of navigation apps for people with different types of disabilities.

1. Introduction

In 2020, over 1 billion people in the world lived with some form of disability and this number is increasing. It is expected that most people will experience a temporary or permanent disability at some point in their lives (WHO, 2020). In the U.S., 61 million adults have some type of disability, which accounts for about a quarter of the country's population (CDC, 2020). Out of these individuals, 4.6% have vision impairments, 5.9% have hearing impairments, 13.7% have mobility impairments, 10.8% have cognitive impairments, and 40% are older adults with disabilities (CDC, 2020).

Wayfinding can be a challenging task for individuals with disabilities. In unfamiliar areas, visually impaired users may have difficulties finding bus stops, benches, and shelters (Hara et al., 2015). Also, they do not always have access to public transportation and rideshares and have difficulty trusting the driver to drop them off at the correct location (Brewer & Kameswaran, 2019). Individuals with cognitive disabilities have difficulty in both orientation and navigation due to their reduced cognitive capability (Gomez et al., 2015). Some may not be able to distinguish the left and right directions and feel confused about matching the landmark pictures with the actual buildings (García de Marina et al., 2012). Thus, they require accompany and supervision of family members or caregivers (Mengue-Topio et al., 2011; Stock et al., 2011). While wheelchair users have used navigations systems to explore outside, finding accessible routes that are totally barrier-free to the wheelchair is still challenging (Harriehausen-Mühlbauer, 2016; Prémont et al., 2020). Additionally, older adults may experience difficulties with some mobile maps because of the inadequate visual saliency, ambiguous affordances, and insufficient amount of information in their design (Yu & Chattopadhyay, 2020).

There has been a limited number of studies clearly defining the wayfinding needs of people with disabilities (Gupta et al., 2020). While there are some studies on navigation for the visually impaired people, there are very few studies for those with mobility or hearing impairment (Ding et al., 2007; Hara et al., 2015; Karimi et al., 2013; Kasemsuppakorn et al., 2015; Menkens et al., 2011). Indoor navigation apps are even more scarce due to situational and technical limitations, such as navigating through stairs and crowded places (Williams et al., 2013). Based on the CDC analyzed data from the family component of the National Health Interview Survey (NHIS) for the years 2011–2014, 22.6 million (11.9%) working-age adults (aged 18–64 years) were found to have any disability, and in this population, 9.8 million (about 43%) had more than one disability type (Stevens et al., 2016). However, there is a lack of design guidelines for navigation apps geared towards people with different types of disabilities (Nielsen, 1996). The objective of this study was to provide guidelines for designing navigation apps that are helpful for people with disabilities. To achieve this objective, we conducted a systematic review of the literature and a scoping view of commercially available assistive apps to understand users' main needs and requirements for such navigation systems.

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There has been a number of literature review studies on navigation devices for people with visual impairment. For example, Kuriakose et al. (2020) conducted a systematic review of literature on tools and technologies for blind and visually impaired individuals. The study was focused on both indoor and outdoor navigation tools and reviewed the underlying technology for those navigation devices in five main categories of visual imagery systems, non-visual systems, map-based systems, systems with 3D sound, and smartphone-based solutions. In addition, the search period was limited to five years (2015–2020). The findings on smartphone-based solutions provided an overview of how these systems work but did not provide any information regarding their interface design features. The recommendations provided by Kuriakose et al. (2020) were general guidelines focusing on the technology and not the interface. This study is different from Kuriakose et al.'s review in scope and coverage of studies, findings, and provided recommendations. Budrionis et al. (2020) conducted another review study on smartphone-based travelling aids for visually impaired individuals. They used both a systematic review methodology and a semi-structured online survey with expert users. Budrionis et al.'s study was focused on purpose and functionality of smartphone-based navigation devices, input/output types, data processing and performance, and usability evaluation methods used in prior studies. One of the gaps identified in Budrionis et al.'s study was the lack of evaluations on existing off-the-shelf navigation solutions. This gap has been addressed in this study by conducting a scoping review and content analysis on commertially available mobile applications. Another literature review study (Khan et al., 2021) provided an overview of different navigation approaches (e.g., e-cane, laser-based walker) and hardware components for obstacle avoidance, and identified some performance metrics for evaluation of these devices (e.g., walking speed, accuracy). Similar to Kuriakose et al. (2020), Khan et al.'s study provided general guidelines on different navigation technologies and not their interfaces. Finally, in a recent review, Al-Razgan et al. (2021) focused on usability of mobile applications for people with visual impairment. Although navigation applications were mentioned in Al-Razgan et al.'s study, the reviewed studies were limited to five years (2015–2020) and the guidelines were general recommendations including eliminating busy graphical interfaces and relying on sounds, use of machine learning approaches to accurately identify the surroundings, and providing real-time updates regarding the upcoming obstacles.

This study is focused on providing guidelines for designing navigation apps that are helpful for people with different types of disabilities. In addition to a systematic review of the literature, we conducted a scoping view and content analysis of commercially available mobile applications to gain insights from the practical application perspective. Furthermore, as compared to prior literature review studies that limited their search to approximately five years without any justification (Al-Razgan et al., 2021; Budrionis et al., 2020; Kuriakose et al., 2020), this study covered a wider range and searched relevant studies published since 2008, when mobile applications gradually became known and popular to the wider public (Strain, 2015).

This article is structured in the following way. In section 2, we introduce the search strategy and inclusion criteria to find relevant studies and apps. Section 3 provides a detailed summary of the review findings. In Section 4, we present the design guidelines that can be used to develop navigation systems for people with disabilities. We also demonstrate how to implement the guidelines in designing the apps. In Section 5, we discuss the conclusions and future work.

2. Approach

To identify the gaps in current assistive navigation application design, we conducted a systematic literature review of relevant scientific papers and a scoping review of commercially available mobile applications. The search included the studies that aimed at finding solutions to improve the interface design and accessibility of navigation applications for people with different types of disabilities. We also reviewed relevant apps to gain insights from the practical application perspective. In our previous work (Zheng et al., 2021), we have conducted a scoping review and content analysis of navigation apps on iOS for blind and visually impaired users. Twenty-eight features were summarized from the analysis of 14 relevant apps and we proposed a set of design recommendations for people with visual impairments based on the analysis. In this work, we expand the search range to apps that are specifically designed for people with other types of disabilities including hearing, mobility, and cognitive impairment, and older adults with disabilities.

2.1. Systematic literature review of scientific studies

The literature review was performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The detailed description of our method including search strategy, eligibility and selection criteria, and data analysis is described below.

2.1.1. Search strategy

The literature search was conducted using databases for science and engineering including Compendex, Web of Science (WOS), ACM Digital Library, IEEE Xplore, Wiley Online, Science Direct, SpringerLink, and Taylor & Francis. Compendex, Science Direct, and IEEE Xplore were used as the most common engineering and technology related databases. Wiley Online and WOS databases were used to search for results across multiple disciplines. ACM digital library database was used as another source due to its coverage of human-computer interaction studies and mobile technologies. Manual search was also conducted in Google Scholar, as it is the most comprehensive search engine and to avoid missing any relevant studies that might not have appeared in the searched databases. Boolean logic (AND, OR) was

Table 1. A list of search terminologies.

Category	Visual	Hearing	Mobility	Cognitive	Older adults
Search terminology	Visual impairment Visually impairment Visually impaired Visually disabled low vision Blind Blindness	Hearing impairment Hearing impaired Hearing loss Deaf hard of hearing	Mobility impairment Mobility impaired Physical impairment Physical disability motor impairment Wheelchair user	Cognitive disability Cognitive impairment Intellectual disability Memory loss	Older adult Older people Elderly Senior people older users

Table 2. Literature search results.

	Category									
	Visual impairment		Hearing impairment		Mobility impairment		Cognitive impairment		Older adults	
Database	Initial	Refined	Initial	Refined	Initial	Refined	Initial	Refined	Initial	Refined
Web of Science	295	6	18	0	255	3	45	3	73	1
Compendex	591	5	45	0	594	2	86	4	124	4
ACM Digital Library	2080	17	266	0	155	2	149	3	363	1
IEEE Xplore	504	6	26	0	331	0	31	3	79	0
Wiley Online	413	2	112	0	50	0	112	0	272	0
Science Direct	945	4	180	0	233	1	262	0	768	1
SpringerLink	6701	3	8	0	1580	1	1619	1	4939	0
Taylor & Francis	312	4	80	0	61	3	71	1	248	0

used to combine the keywords of *navigation* and *user interface*, with each of the "terminologies" listed in Table 1. For example, for visual impairment, the search string included: (*navigation*) AND (*user interface*) AND (*visual impairment* OR *visually impairment* OR *visually impaired* OR *visually disabled* OR *low vision* OR *blind* OR *blindness*). The search was focused on finding relevant studies published since 2008, when mobile applications gradually became known and popular to the wider public (Strain, 2015).

2.1.2. Inclusion and exclusion criteria

The inclusion criteria used in this study were: (1) articles written in English and published in peer-reviewed journals, conference proceedings, and books, and (2) studies that focused on designing or providing guidance to make the mobile interfaces user-friendly and accessible to people with disabilities. Note that we have excluded papers that focused on the technology rather than the design since the aim of this study was to formulate a set of design guidelines that can improve the interfaces for navigation applications.

2.1.3. Search results

The literature search was completed by May, 2022. In the initial search, 25,076 articles were identified to potentially be relevant to the study based on the set of keywords. After reviewing the titles and abstracts, the full text of the papers that were identified to be relevant were reviewed by the authors independently. Table 2 shows the detailed search results of the initial numbers of articles found in each database for each type of disability and the number of articles identified to be relevant to the current work after the full review. After removing the duplicated studies among the databases, 65 unique studies were found to meet the inclusion criteria and were included in this review. The detailed findings and conclusions of the 65 relevant articles are discussed in Section 3.1.

2.2. A Scoping review and content analysis of commercially available mobile applications

Two types of mobile apps were reviewed including: (1) navigation apps that are specifically designed for people with hearing impairment, mobility impairment, cognitive impairment, or older adults; and (2) apps designed for individuals with disabilities in areas other than navigation. Note that navigation apps for blind or visually impaired people have been excluded in this review since they have been provided in detail in our previous study (Zheng et al., 2021). However, we included those apps that targeted users with multiple disabilities (e.g., hearing impairmed and visually impaired users). We included a review on apps designed for individuals with disabilities in other domains to capture general usability principles and design requirements that might be applicable to the design of navigation apps for this population.

2.2.1. Search of assistive navigation apps

The terminologies used to find navigation apps that can assist people with disabilities are listed in Table 3. The keywords included *navigation*, *guide*, and *wayfinding* in combination with the associated terms that describe the specific types of disability. All searches were conducted in the Apple iOS app store and Googly play store and were completed in May 2022. In total, 180 apps were identified from the initial search. After removing the duplicated apps and apps without accessibility (need to be purchased or need to be used at a precise location), 161 unique apps were selected for further review on titles and app descriptions. Based on the screening of titles and descriptions, we excluded those apps that were not written in English, and were not relevant in assisting older adults or people with cognitive, hearing, or mobility impairments to fulfill the wayfinding task. Fifty-two apps were downloaded to interact with for further assessment. In the end, we found 15 navigation apps for people with mobility impairment and one navigation app for older adults.

Table 3. Navigation apps search: Search terminologies and results.

Search terminology	Initial	Screened	Refined
navigation + hearing impairment	48	18	0
guide + hearing impairment			
wayfinding + hearing impairment			
navigation + hearing loss			
guide + hearing loss			
wayfinding + hearing loss			
navigation + deaf			
guide + deaf			
wayfinding + deaf			
navigation + hard of hearing			
guide + hard of hearing			
wayfinding + hard of hearing			
navigation + mobility impairment	89	17	15
guide + mobility impairment			
wayfinding + mobility impairment			
navigation + motor impairment			
guide + motor impairment			
wayfinding + motor impairment			
navigation + wheelchair			
guide + wheelchair			
wayfinding + wheelchair			
navigation + cognitive impairment	22	9	0
guide + cognitive impairment			
wayfinding + cognitive impairment			
navigation + cognitive disability			
guide + cognitive disability			
wayfinding + cognitive disability			
navigation + older adult	21	8	1
guide + older adult			
wayfinding + older adult			
navigation + older people			
guide + older people			
wayfinding + older people			
navigation + elderly			
guide + elderly			
wayfinding + elderly			

Table 4. Mobile apps for other applications: Searched terminologies and results.

Category	Terminology	Initial	Refined
Hearing impairment	Hearing impairment	580	25
	Hearing loss		
	Deaf		
Cognitive impairment	Cognitive impairment	176	1
	Cognitive disability		
Older adult	Older adult	215	6
	Older people		
	Elderly		

However, we did not find any navigation apps that could provide instant support to people with cognitive impairments or hearing impairment.

2.2.2. Search of apps designed for disabled or older adults

Since there was no or very few navigation apps specifically designed for older adults or people with cognitive or hearing impairment, we extended our search and analysis with apps that support these users for other daily activities or communication. The search keywords and results are listed in Table 4. All searches were completed in May, 2022. The initial search led to 971 apps, which was then filtered based on the criteria of availability, English version, relevancy, date (have been updated within three years), and duplication. Finally, 32 additional apps were found to be relevant. However, three apps targeted people with multiple disabilities (i.e., MAVIS, Accessible Jordan, and BillionAbles). Therefore, 45 unique apps (including the navigation apps presented in Table 3) were included to conduct the content analysis (described in Section 2.2.3).

2.2.3. Qualitative content analysis

To understand the design insights and features of the selected assistive apps, we conducted a qualitative content analysis including the following four phases:

1. Coding the basic descriptive information for each app, including the app name, developer, version, latest updated date, rating, number of reviews, supporting languages, target user groups, and application;
2. Interpreting the written descriptions, screenshot demos, available user reviews of apps, and the version updating reports provided by the developers;
3. Developing a preliminary framework to organize a list of design features; and
4. Revising and grouping the identified features based on the interaction with apps.

3. Results

3.1. Summary of literature review findings

The characteristics of the reviewed studies are summarized in Table 5 with a focus on the target user group, modality of information presentation, methods, and applications.

Table 5. Summary of relevant studies on assistive navigation application design and development.

No.	References	User group	Modality	Methods	Application
1	Rodriguez-Sanchez et al. (2014)	Blind or visually impaired users	Visual (text, map), auditory and tactile feedback, touchscreen	Literature review; User testing	Outdoor navigation
2	Gallagher et al. (2014)	Blind or visually impaired users	Visual (text, arrow), tactile feedback in default, audio feedback when requested	Review of indoor navigation research products for blind and visually impaired users; Usability evaluation	Indoor navigation
3	Als et al. (2018)	Blind or visually impaired users	Audio, visual (text, icon, unique color scheme, map), and vibration feedback	Survey and questionnaires; user testing	Outdoor navigation
4	Giudice et al. (2019)	Blind or visually impaired users	Visual, spatialized audio, and haptic or vibration cues; speech input enabled	User testing	Indoor navigation
5	Nair et al. (2020)	Blind or visually impaired users	Audio, visual, and vibrotactile feedback with different levels (e.g., information density and vibration intensity)	Usability evaluation; Performance study	Indoor navigation
6	Harriehausen-Mühlbauer (2016)	Mobility impaired users	Visual, audio feedback; speech input, keyboard input	User testing	Indoor and outdoor navigation
7	Prémont et al. (2020)	Mobility impaired users	Not applicable	Scoping review	Outdoor navigation
8	Liu et al. (2008)	Cognitive impaired users	Visual (arrow, photo of landmarks, photo with highlight area, text message), audio message	Wizard-of-Oz; usability evaluation	Indoor navigation
9	Liu et al. (2009)	Cognitive impaired users	Visual (arrow, photo of landmarks, photo with highlight area, text message), audio message	User testing	Outdoor navigation
10	Gomez et al. (2015)	Cognitive impaired users	Visual (arrow, street-level photos, text), audio, vibrate feedback	User-centered design; User testing; Comparison analysis with another commercial navigation app	Outdoor navigation
11	Gomez and Montoro (2015)	Cognitive impaired users	Visual (arrow, street-level photos, text)	Literature review; usability evaluation	Outdoor navigation
12	Jian et al. (2012)	Older adults	Visual, audio feedback; touch and speech input	User testing	Indoor navigation
13	Sili et al. (2017)	Older adults, blind or visually impaired users	Visual, tactile, and voice feedback; touchable input	User-centered design; interview with caregivers and facility staff members; user experience evaluation	Indoor and outdoor navigation
14	Comai et al. (2017)	Older adults, cognitive impaired users, mobility impaired users	Visual (text, image, arrow, map) and audio feedback; touchable input	User testing	Indoor navigation
15	Fickas et al. (2008)	Cognitively impaired users	Bird view and point of view images, audio directions without image, text-based instructions without image	User/field testing	Outdoor navigation
16	Chang et al. (2010)	Cognitively impaired users	Images overlaid with arrows and text-based information	User/field testing	Indoor navigation
17	Stent et al. (2010)	Visually impaired (low vision) users	Speech-based input; audio, text, and tactile output	Concept paper	Outdoor navigation
18	Kacorri et al. (2018)	Visually impaired users	Speech and text	Review of data logs from an app	Outdoor navigation
19	Guerreiro et al. (2019)	Visually impaired users	Audio instructions	Focus group and user testing	Indoor navigation
20	Angeletou et al. (2013)	Older adults	Audio-based instruction; visual navigation	Focus group, questionnaire, observation, interview, and brainstorm	Outdoor navigation
21	Sato et al. (2019)	Visually impaired users (blind or low vision)	Audio-based instructions; visual display	User testing, focus group	Indoor navigation
22	Jafari (2019)	Deaf and hard of hearing users	Text to speech; visual interface; vibration	Survey, interview, user testing	Indoor navigation
23	Chang, Chen, et al. (2008)	Cognitively impaired users	Visual images; alerts when deviation from a path occurs	User testing, survey	Indoor navigation
24	Chang, Chu, et al. (2008)	Cognitively impaired users	Visual images	User testing, survey	Indoor navigation
25	Chang et al. (2009)	Cognitively impaired users	Videos (both visual and audio based information)	User testing, survey	Indoor navigation
26	Cheraghi et al. (2017)	Blind and visually impaired users	Voice; audio; haptic (vibrating alerts when deviation from a path occurs)	User testing	Indoor navigation
27	Kim et al. (2014)	Visually impaired users	Simple touch, audio instructions	Prototype	Indoor and outdoor navigation

(continued)

Table 5. Continued.

No.	References	User group	Modality	Methods	Application
28	Somyat et al. (2018)	Visually impaired users	Audio instructions	Prototype	Outdoor navigation
29	Ganz et al. (2014)	Visually impaired users	Touch-based interaction	Prototype	Indoor navigation
30	Prerana et al. (2019)	Visually impaired users	Touch screen; voice inputs; audio instructions	Prototype	Outdoor navigation
31	Paladugu et al. (2013)	Visually impaired users	Accessible touch screen (using gestures such as double tap to select); voice input; verbal descriptions	User testing	Outdoor navigation
32	Chang, Tsai, et al. (2008)	Cognitively impaired users	Visual images and directions	User testing	Indoor navigation
33	Krainz et al. (2016)	Visually impaired users, Cognitively impaired users, older adults	Touch-based intraction	User testing, survey	Outdoor navigation
34	Arenghi et al. (2018)	Visually impaired users, mobility impaired users	Visual; auditory	User testing, interview	Outdoor navigation
35	Cheraghi et al. (2019)	Visually impaired users, mobility impaired users	Visual; auditory; haptic	User testing	Indoor navigation
36	Ivanov (2010)	Visually impaired users	Audio-based navigational instructions	Interview	Indoor navigation
37	Yang et al. (2011)	Visually impaired users	Audio instructions; five simple touch gestures	User testing, interview	Indoor navigation
38	Guy and Truong (2012)	Visually impaired users	Touch screen; audio instructions; speech-based data entry	Formative interviews, user testing	Outdoor navigation
39	Jain et al. (2013)	Visually impaired users	Audio-based navigational instructions	User testing, interview	Indoor navigation
40	Jain (2014b)	Visually impaired users	Visual; audio; vibration (vibrating alerts when deviation from a path occurs)	Pilot test	Indoor navigation
41	Ryu et al. (2014)	Visually impaired users	Audio-based navigational instructions	Protype	Indoor navigation
42	Chen et al. (2015)	Visually impaired users	Visual; audio; vibration	Interview, user testing	Outdoor navigation
43	Kim et al. (2016)	Visually impaired users	Touch screen (simple gestures); auditory instructions	User testing	Indoor navigation
44	Ahmetovic et al. (2016)	Visually impaired users	Touch screen; auditory instructions	User testing	Indoor and outdoor navigation
45	Eskicioglu et al. (2020)	Visually impaired users	Voice commands; manual input; auditory instructions	Heuristic evaluation	Outdoor navigation
46	Chatzina and Gavalas (2021)	Visually impaired users	Touch screen; auditory intstructions; voice-based inputs; haptic feedback when buttons were pressed	User testing	Outdoor navigation
47	Firmino and Teófilo (2013)	Visually impaired users	Audio-based navigational instructions	User testing	Indoor navigation
48	Jain (2014a)	Visually impaired users	Visual, audio, and vibration (vibrating alerts when deviation from a path occurs)	Formative interviews, user testing	Indoor navigation
49	Constantinescu et al. (2019)	Visually impaired users	Audio-based navigational instructions	User testing	Outdoor navigation
50	Griffin et al. (2020)	Visually impaired users	Audio and tactile navigational instructions	User testing, interview, survey	Indoor navigation
51	Coughlan and Manduchi (2009)	Visually impaired users	Audio-based navigational instructions	User testing	Indoor navigation
52	Lewis et al. (2015)	Visually impaired users	Audio-based navigational instructions	Focus group	Indoor and outdoor navigation
53	Brock et al. (2012)	Visually impaired users	Touch screen (simple gestures); text-to-speech capability	User testing, survey	Outdoor navigation
54	Chaudary et al. (2021)	Visually impaired users	Haptic and voice-based communication	User testing, survey, interview, group discussion	Indoor and outdoor navigation
55	Long et al. (2016)	Visually impaired users	Visual; screen reading software	User testing, interview, questionnaire	Outdoor navigation
56	Kahraman and Turhan (2021)	Visually impaired users	Visual; audio-based navigational instructions; vibration (vibrating alerts when deviation from a path occurs)	User testing, questionnaire	Indoor navigation
57	Barbosa et al. (2018)	Mobility impaired users	Visual; Touch-based intraction	User testing, surevy	Indoor and outdoor navigation
58	Harriehausen-Muhlabauter (2014)	Mobility impaired users	Visual; Touch-based intraction	User testing	Outdoor navigation

(continued)

Table 5. Continued.

No.	References	User group	Modality	Methods	Application
59	Karimi et al. (2014)	Mobility impaired users	Screen reader; audio and tactile communication; visual feedback	Prototype	Outdoor navigation
60	Chang and Wang (2010b)	Cognitively impaired users, Mobility impaired users, Visually impaired users	Visual; auditory	User testing, interview	Indoor navigation
61	Al-Khalifa and Al-Razgan (2016)	Visually impaired users	Voice commands and auditory navigational information; touchscreen	User testing, interview	Indoor navigation
62	Chang and Wang (2010a)	Cognitively impaired users	Visual images; videos	User testing, survey	Indoor navigation
63	García-Catalá et al. (2020)	Cognitively impaired users	Visual; auditory	Literature review, prototype	Indoor navigation
64	Rodriguez-Sánchez and Martinez-Romo (2017)	Visually impaired users, Hearing impaired users, mobility impaired users, people with no disability	Text; visual maps; auditory and tactile feedback	User testing, questionnaire	Indoor and outdoor navigation
65	Moreno et al. (2012)	Visually impaired users	Speech recognition system; auditory information	Prototype	Indoor and outdoor navigation

3.1.1. User group

Among the 65 studies, 44 papers focused on wayfinding solutions specifically for people with visual impairment, 10 were related to enhancing the navigation capabilities for mobility impaired users, 15 studies designed interfaces to better navigating people with cognitive impairment, 5 were focused on designing interfaces for older adults, and 2 studies proposed solutions for individuals with hearing impairment (found through manual search in Google Scholar). It is important to note that some studies targeted people with multiple disabilities (Comai et al., 2017; Krainz et al., 2016).

3.1.2. Modality of information presentation

A majority of studies used visual interfaces to provide navigational information. However, for visually impaired users, these interfaces were combined with auditory and/or haptic cues. Most studies agreed that audio feedback is essential to include in the design. Eighteen studies provided haptic or vibration feedback. This feedback was provided when the users pressed a button or deviated from a correct path. Among all of these studies, 13 interfaces supported voice command features to allow the users to speak to the system directly.

3.1.3. Methods

All of the studies except for Prémont et al. (2020) and a few concept or prototyping papers (Ganz et al., 2014; Kim et al., 2014; Prerana et al., 2019; Ryu et al., 2014; Somyat et al., 2018; Stent et al., 2010), recruited end-users of the target group and conducted usability evaluations to validate their concepts or applications. While some studies have conducted reviews of other navigation products to propose a set of design recommendations and applied those criteria to their designs, others presented details on how they have applied the user-centered design process to elaborate the use cases and scenarios that proceeded to the final design. The most common usability evaluation method used in these studies was user/field testing in which the end users were asked to use the interface for navigating through indoor or outdoor environments and the experimenter evaluated their performance and captured their subjective evaluation of the interface (using surveys or interviews at the end of the study).

3.1.4. Applications

From the 65 studies, 9 studies supported both indoor and outdoor navigations, 32 studies were designed specifically for indoor navigation, and 24 studies were designed specifically for outdoor navigation. Indoor navigation devices were tested in various applications including navigating in public places such as museums, shopping malls, airports, train stations, and university buildings.

3.1.5. Design guidelines for assistive navigation applications

In this work, the 10 heuristic design principles proposed by Molich and Nielsen (1990) were used as a reference to identify possible solutions for designing navigation systems including the principles of: visibility of system status (i.e., keep the users be aware of the system status), match between system and the real world (i.e., use words, phrases, and concepts familiar to the user), user control and freedom (i.e., allow the users to leave unwanted action), consistency and standards (i.e., follow standards and conventions), error prevention (i.e., prevent problems from occurring in the first place), recognition rather than recall (i.e., minimize the user's memory load), flexibility and efficiency of use (i.e., use shortcuts to tailor frequent actions), aesthetic and minimalist design (i.e., exclude all irrelevant information), help users recognize, diagnose, and recover from errors (i.e., indicate the problem and suggest a solution), and help and documentation (i.e., provide assistance and documentation to help the user understand how to complete their tasks). Based on these principles, a list of design guidelines was generated from the literature review and was summarized in Table 6 along with their references. These design guidelines

Table 6. The systematic literature review: Summary of design guidelines for each type of disabilities.

	Visual	Hearing	Motor	Cognitive	Older adults	Nielsen's Principle
Modality design consideration						
(1) Enable multiple sensory channels (visual, auditory, and tactile) to provide information and communication. Allow the users to select their preferred modalities (Gallagher et al., 2014; Rodriguez-Sanchez et al., 2014).	*	*	*	*	*	Aesthetic and minimalist design
(2) Enable voice control to allow the users to interact with the system with voice commands (Giudice et al., 2019; Jian et al., 2012).	*		*	*	*	Aesthetic and minimalist design
(3) Include voice control and speech dialogue for users that are not able to manually interact with the navigation system (Harriehausen-Mühlbauer, 2016). Avoid heavy text input actions as much as possible (Jian et al., 2012).			*			Aesthetic and minimalist design
(4) Use vibrating alerts when the user deviates from the path (Chang, Chen, et al., 2008; Cheraghi et al., 2017; Jain, 2014a)	*			*		Error prevention
(5) Combine audio and vibration feedback in case that the blind user could not hear the audio of the application clearly in a noisy environment (Rodriguez-Sanchez et al., 2014)	*					Aesthetic and minimalist design
Visually-based interface design						
(6) Keep the design simple with few or no overlapping items (Gomez & Montoro, 2015; Jian et al., 2012).	*	*	*	*	*	Aesthetic and minimalist design
(7) Design all GUI items with proper shapes, sizes, and spaces (Jian et al., 2012).	*	*	*	*	*	Aesthetic and minimalist design
(8) Use unified or similar fonts, colors and sizes when displaying texts (Jian et al., 2012).	*	*	*	*	*	Aesthetic and minimalist design
(9) Avoid unnecessary and irrelevant visual effects (Jian et al., 2012).	*	*	*	*	*	Aesthetic and minimalist design
(10) Customize color contrasts for better readability (Jian et al., 2012).	*	*	*	*	*	Aesthetic and minimalist design
(11) Use simple and easily recognizable shape designs (Jian et al., 2012).	*	*	*	*	*	Match between system and the real world
(12) Use unique color scheme to differentiate specific situations (Als et al., 2018).	*	*	*	*	*	Consistency and standards
(13) Avoid sole usage of colors or images to convey information (Jian et al., 2012).	*	*	*	*	*	Aesthetic and minimalist design
(14) Emphasize changes on the user interface in an obvious and observable way (Jian et al., 2012).	*	*	*	*	*	Visibility of system status
(15) Choose proper palette for color blindness. Try monochromatic color schemes (Gomez & Montoro, 2015).	*					Flexibility and efficiency of use
(16) Use simple language without abbreviations (Krainz et al., 2016)	*			*		Match between system and the real world
(17) Important features should be visible without scrolling (Krainz et al., 2016)	*			*		Visibility of system status
(18) Make all texts and icons large enough to be readable on the communicating interfaces (Jian et al., 2012).	*				*	Aesthetic and minimalist design
Audio-based interface design						
(19) Keep messages short and allow interruptions (Firmino & Teófilo, 2013; Jian et al., 2012).	*		*	*	*	Flexibility and efficiency of use
(20) Design appropriate pauses since the timeliness of prompts is crucial (Liu et al., 2008).	*		*	*	*	Flexibility and efficiency of use
(21) Use distinct audible tone to differentiate specific situations for blind users (Jian et al., 2012).	*					Consistency and standards
(22) Design verbal messages to be spatially determinant, such as "turn left when you hear the water flowing of fountain," "stop when you feel carpet under foot" (Giudice et al., 2019).	*					Visibility of system status
(23) Build the vocabulary with more definite articles, auxiliaries, first person pronouns and lexical items related to social interaction (Jian et al., 2012).	*		*	*	*	Consistency and standards
(24) Design synthesized texts and standardized instruction suitable for the users regarding style, vocabulary, grammar, length and sentence structures (Constantinescu et al., 2019; Jian et al., 2012).	*	*	*	*	*	Match between system and the real world
(25) Adapt the dialogue strategies to satisfy the needs of older adults and people with mobility impairment, such as to understand the shaky or broken speech (Jian et al., 2012).				*	*	Error prevention
(26) Use low-pitched voices for speech synthesis for elderly users (Jian et al., 2012).					*	Aesthetic and minimalist design
(27) Provide auditory feedback when approaching obstacles or destination (Jain, 2014a; Lewis et al., 2015)	*					Visibility of system status
(28) Use simple commands specifying the direction and exploiting landmarks such as doors and corridors (Comai et al., 2017).	*		*	*	*	Flexibility and efficiency of use

(*continued*)

Table 6. Continued.

	Visual	Hearing	Motor	Cognitive	Older adults	Nielsen's Principle
Tactile-based interface design						
(29) Use fixed regions when designing interfaces (Rodriguez-Sanchez et al., 2014).	*	*	*	*	*	Consistency and standards
(30) Use simple gestures (e.g., tap, double tap) (Griffin et al., 2020; Kim et al., 2014; Paladugu et al., 2013)	*					Match between system and the real world
(31) Use gestures that can be performed with one hand (Yang et al., 2011)	*					User control and freedom
(32) Use various but fixed vibration patterns to indicate different situations (Als et al., 2018).	*	*	*	*	*	Consistency and standards
(33) The level of vibration should depend on the proximity to the destination, landmark, or obstacle (Rodriguez-Sánchez & Martinez-Romo, 2017).	*	*	*			Error prevention
Information display and communication						
(34) Provide clear and repeated turn-by-turn instructions (Gallagher et al., 2014; Sili et al., 2017).	*	*	*	*	*	Visibility of system status
(35) Use turn-based directions to navigate is easier than landmark-based directions (Liu et al., 2009).	*	*	*	*	*	Error prevention
(36) Incorporate description and identification of landmarks (Gallagher et al., 2014; Lewis et al., 2015).	*	*	*	*	*	Visibility of system status
(37) Provide landmark names to help the user to remember the unfamiliar landmarks for future use (Liu et al., 2009).	*	*	*	*	*	Visibility of system status
(38) Present landmark pictures to help users visually identify the location of points (Gomez et al., 2015).	*	*	*	*	*	Visibility of system status
(39) Offer multiple densities of information to different users. Blind users might need the densest amount of feedback and instructions compared to other users (Nair et al., 2020).	*	*	*	*	*	Aesthetic and minimalist design
(40) Provide real-time information (street signs, pedestrian crossing, route instructions) and appropriate confirmations (feedback) in proper frequency to the users, and alert users about the physical references (obstacles) (Giudice et al., 2019; Gomez et al., 2015; Rodriguez-Sanchez et al., 2014).	*					Visibility of system status
(41) Divide the route into simpler steps to help people with cognitive disability better understand the instructions (Gomez et al., 2015).				*		Error prevention
(42) Present a street-level landmark photograph with every instruction to assist people with cognitive disability better identify the location of points, as well as the directions. Combine the instructions with real images of the landmarks (Gomez et al., 2015; Gomez & Montoro, 2015).				*		Visibility of system status
(43) Deliver the direction instructions in appropriate time and speed (avoid delays, or too quick, too close instructions) (Liu et al., 2009; Sili et al., 2017).	*	*	*	*	*	Visibility of system status
(44) Show progress bar to users to illustrate how far the user is from the shown destination point (Gomez et al., 2015).	*	*	*	*	*	Visibility of system status
(45) Provide the option of moving forward to the next step or backward to see a previous instruction via one click (Gomez et al., 2015; Sili et al., 2017).	*	*	*	*	*	User control and freedom
System automated assistant						
(46) Measure and guide to ensure the user is facing the correct direction (Nair et al., 2020).	*	*	*	*	*	Error prevention
(47) Detect user deviations and realign the path for users (Comai et al., 2017; Gomez & Montoro, 2015; Nair et al., 2020).	*	*	*	*	*	Help users recognize, diagnose, and recover from errors
(48) Compute a detour in case the chosen route does not work, e.g., when the route contains barriers (Harriehausen-Mühlbauer, 2016).	*	*	*	*	*	Help users recognize, diagnose, and recover from errors
Adaptation to user's needs						
(49) Allow for customization of size and type of wheelchair (e.g., active wheelchair users, electric wheelchair users, wheelchair users that have an assistant) (Harriehausen-Muhlabauter, 2014; Harriehausen-Mühlbauer, 2016).	*	*	*	*	*	Flexibility and efficiency of use
(50) Allow for customization of the user profiles (individual physical conditions and limitations such as the number of stairs that can be mastered) (Harriehausen-Mühlbauer, 2016).			*			Flexibility and efficiency of use
(51) Plan and schedule users' paths and activities based on their specific needs, e.g., avoid stairs (Comai et al., 2017).			*			Flexibility and efficiency of use
(52) Adapt route calculation by including places that are well-known to the user instead of delivering the shortest or fastest route (Gomez et al., 2015; Hervás et al., 2014).				*		Flexibility and efficiency of use
Preferences and support						
(53) Offer help instantly with the user's preferred way and preferred contacts (Gomez et al., 2015).	*	*	*	*	*	Flexibility and efficiency of use

(*continued*)

Table 6. Continued.

	Visual	Hearing	Motor	Cognitive	Older adults	Nielsen's Principle
(54) Provide options for users to choose their preferred mode of interaction, language, customized frequency and speed of speech instructions, sound, unit of distance, etc. (Cheraghi et al., 2019; Griffin et al., 2020; Lewis et al., 2015)	*		*			User control and freedom
(55) Include distant unit preference in imperial (feet), metric (meters), in steps, or in general (Gallagher et al., 2014; Giudice et al., 2019).	*	*	*	*	*	Consistency and standards
Other considerations						
(56) Present the user with a list of the possible destination points (previously created list) to choose from. Do not require them to input the address manually (Gomez et al., 2015; Gomez & Montoro, 2015).	*	*	*	*	*	Recognition rather than recall, flexibility and efficiency of use
(57) Use text displays when auditory information is missed- or not heard (Jian et al., 2012).	*		*	*	*	Error prevention
(58) Instruct the users with visual impairment to find the buttons of the elevator and notify them when the elevator doors open (Nair et al., 2020).	*					Visibility of system status
(59) Allow for the inclusion of both static as well as temporary barriers (Harriehausen-Mühlbauer, 2016).			*			Visibility of system status
(60) Mark the barriers such as steep ramps, stairs, bouldering, and other uneven footpath surfacing on a chosen route (Harriehausen-Mühlbauer, 2016).			*			Visibility of system status
(61) Provide easy access to the caregiver to edit destination for the users (Gomez et al., 2015).				*	*	Error prevention
(62) Provide communication and supervision tool to user's caregivers and relatives (Gomez & Montoro, 2015).				*	*	Help users recognize, diagnose, and recover from errors
(63) Provide online and offline mode to access the information and navigation anywhere and anytime (Rodriguez-Sanchez et al., 2014).	*	*	*	*	*	Flexibility and efficiency of use
(64) Include a "where am I?" function to allow the users scan their environment and see what is around them (Lewis et al., 2015).	*					Recognition rather than recall
(65) Display routes with and without barriers and identify the type of barrier (Harriehausen-Muhlabauter, 2014).			*			Visibility of system status

were categorized into nine groups. We have identified the types of disabilities that would greatly benefit from the implementation of each design guideline. In addition, the design guidelines are matched to the categories of Nielsen's principles (Nielsen, 1994). In the following paragraphs, we discussed these design guidelines in detail. It is important to note that these guidelines should be considered in addition to the general guidelines for mobile devices (Li & Luximon, 2020; Patch et al., 2015).

Modality design considerations. the modality of information presentation and communication is a critical feature and should be adapted to users' needs and preferences (Gallagher et al., 2014; Rodriguez-Sanchez et al., 2014). The use of appropriate input and output modalities can ensure that the information would be conveyed effectively. For example, enabling the voice commands and avoiding the manual interaction with the system as much as possible will help free the hands of motor disabled users to push their wheelchairs. Audio and tactile cues can notify blind or visually impaired users when it is time to make a turn. For individuals with hearing impairment, a combination of visual and tactile feedback should be used to alert them and a combination of audio and vibration feedback can be a good solution when a blind user could not hear the audio from the application in noisy environments (Rodriguez-Sanchez et al., 2014). Thus, the system should support multiple modalities for providing landmark information, navigating instructions, and communications based on user groups and preferences.

Visual-based interface design. in this category, we summarized several guidelines that focus on utilizing visual communication to effectively deliver information to the users. To increase the readability of the system, all the visual designs and layout should be simple (Gomez & Montoro, 2015; Jian et al., 2012). All graphical user interface (GUI) items should be adjusted to proper shapes, sizes, and put in proper locations (Jian et al., 2012). The important display features should be visible without the need for scrolling. The overlap between items should be minimized, all text should be displayed with a unified design style (in fonts, colors, and sizes), and any irrelevant visual effects should be excluded to catch the user's attention (Jian et al., 2012). In addition, strong color contrast usually comes with better readability (Jian et al., 2012). The more effective and accurate the interfaces can display the content, the better the users understand and interact with the system. It is recommended to use shapes and icons that are easy to be recognized (Jian et al., 2012). The metaphor icons can help the users to build the natural mapping and understand the functionality behind the button quickly. For example, use the microphone icon to take voice inputs from the user, use the five-pointed star icon to save the favorite items, use the shopping cart icon to represent the placeholder for the grocery store, etc. While the use of unique color schemes can assist in differentiating different modes of the system, it is better to avoid using colors or pictures alone to convey information (Jian et al., 2012). Text description is needed to better introduce the system context. When the user interacts with the system, it is also effective to timely provide visual cues to the users to be aware of the changes (e.g., change the color of a button while the user presses it). In addition, to assist individuals with color blindness or any adults with visual impairment, it is necessary to choose a proper palette such as monochromatic color schemes (Gomez & Montoro, 2015). All essential visual cues such as texts and icons should be large enough to be readable on the screen specifically for people with visual impairment (Jian et al., 2012).

Audio-based interface design. the audio instructions should use language and terms that are intuitive and familiar to the users. The text should be adapted to different user groups regarding the style, vocabulary, length, and sentence structures (Jian et al., 2012). In addition, the voice message should be short, with proper pauses between two auditory feedback, and allow for interruptions (Firmino & Teófilo, 2013; Jian et al., 2012). Consistent and distinct audible tones should be used to indicate the different situations (Jian et al., 2012). This design will specifically benefit people with visual impairment in differentiating the specific situations. In addition, incorporating the description and distinguishing characteristics of landmarks will help the user identify and recognize them better (Giudice et al., 2019). Especially for blind users, the use of spatially determinant audio messages such as "stop when you feel the carpet underfoot" to provide additional navigation instructions will be helpful. For recognizing the speech input by the users, the vocabulary should be built with more natural language during daily social interactions. It is recommended to include synthesized texts, standardized instructions, and dialogue structures to cope with the specific needs and customization of different groups of users (Constantinescu et al., 2019; Jian et al., 2012). Especially for older adults and for people with mobility impairments, there is a need to support fuzzy recognition of voice inputs to cope dialogue strategies with their specific needs such as repeating and shaky speech. Older adults prefer to interact with low-pitch voices of speech synthesis (Jian et al., 2012). Furthermore, simple commands should be used to specify directions and explore landmarks for all types of users (Comai et al., 2017).

Tactile-based interface design. Structuring the user interface with fixed regions is especially helpful in reducing the cognitive workload of users (Rodriguez-Sanchez et al., 2014). Simple gestures are recommended, such as taping or double tapping (Kim et al., 2014; Paladugu et al., 2013). It is necessary to use various but fixed vibration patterns to indicate different situations (Als et al., 2018). This can be particularly helpful for blind people to receive feedback accurately. Furthermore, the gestures should be simple enough so they can be performed with one hand and the user can hold a cane or a guide dog with another hand (Yang et al., 2011).

Information display and communication. in general, clear and repeated turn-by-turn instructions in addition to information on landmarks should be provided (Gallagher et al., 2014; Sili et al., 2017). The use of turn-based directions has been identified to be easier to follow than landmark-based directions since the user can better understand the instructions that divide the route into simpler steps and does not have to remember the details of navigation (Liu et al., 2009). In addition, it is beneficial to incorporate the landmark name, description, and photo to help the user better identify the location and remember the unfamiliar landmarks for future use (Gomez et al., 2015; Liu et al., 2009). However, multiple densities of information should be provided to different users based on their needs (Nair et al., 2020). For example, people who are blind require more details and real-time information regarding the objects around them such as street signs, doors, pedestrian crossing, and obstacles. They need the densest amount of feedback and instructions to navigate compared to other users. For people with cognitive impairment, they can better understand the route instruction if the navigating massage has been divided into simpler steps (Gomez et al., 2015). They can also navigate better if the instruction is combined with a street-level photo of the landmark (Gomez et al., 2015; Gomez & Montoro, 2015). Another crucial factor in delivering instruction effectively is the timeline. The system should timely notify the users about the surrounding situation, and deliver the turn-by-turn instructions in proper frequency and speed without delay (Liu et al., 2009; Sili et al., 2017). Letting the user be aware of the system status with a progress bar can also be beneficial. Information regarding the travel progress should be provided to let the user know how far they are from the shown destination point. For example, the interface can visually display or read the estimated arrival time and distance of travel to the users. It might also be beneficial to allow the user to move forward to pre-view the next step and move back to check the previous instructions using one-click or voice command so that the user feels more control and freedom in using the application (Gomez et al., 2015; Sili et al., 2017).

System automated assistant. the system should always measure and prevent the user from deviation (Comai et al., 2017; Gomez & Montoro, 2015; Nair et al., 2020). For example, by prompting instant feedback to make sure the user is facing the correct direction. If the user is heading the wrong way, the system should be able to detect the deviation, send real-time reminders, and timely realign the path for the user. In case when the original chosen route does not work, the system should also have the capability of computing a detour for the users (Harriehausen-Mühlbauer, 2016).

Adaptation to user's needs. the system should be adaptable according to users' needs and preferences. For people with mobility impairment, the system should allow them to customize their user profiles by inputting the size and type of the wheelchair, or recording the individual physical condition (Harriehausen-Mühlbauer, 2016). Thus, the system can search and plan suitable places and special routes based on the size and type of the user's wheelchair and with their movement capabilities. In addition, instead of delivering the shortest and fastest route to them, the system should present a route that includes the places that are well-known to this group of users to reduce cognitive workload (Gomez et al., 2015; Hervás et al., 2014).

Preferences and support. instant help should be provided to users (Gomez et al., 2015). For example, they could make a selection of whether to contact their family or care providers for help with video or audio calls. For preference setting, the system should allow the users to select their preferred modalities, or preferred distant unit when receiving the navigation instructions (Gallagher et al., 2014; Giudice et al., 2019).

Other considerations. in this category, we have included a few more solutions that are designed for people with disabilities. Generally, the system should provide category and nearby search queries. Instead of asking the user to input address manually, the system should assist the users to recall than remember by presenting a list of the possible destination points to choose from (e.g., search by restaurants, grocery stores, or departments and offices in a building) (Gomez et al., 2015; Gomez & Montoro, 2015). Text displays can help when auditory information is missing or cannot be heard (Jian et al., 2012). Note that this alternative solution is only effective for people who can hear and rely on receiving information using auditory feedback. It would be beneficial to include a feature that helps visually impaired people to accurately locate the buttons of the elevator and notify them when the elevator doors open (Nair et al., 2020). The live sharing and updates on barrier information and route accessibility will benefit the whole community, especially for people with mobility impairment. The system should allow the user to report the existing or absence of physical references such as obstacles and architectural barriers in real-time (Harriehausen-Mühlbauer, 2016). This feature needs the system to be enabled with the barrier markers for both permanent and temporary existing barriers. For older adults or cognitively impaired people who may need assistance from their caregivers and relatives, the system should give those caregivers and relatives easy access to edit destinations for the users, and to supervise and communicate with them (Gomez et al., 2015). Finally, if both online and offline modes are available, the users will be able to access the information and navigate anywhere and anytime without the need of worrying about the internet connection (Rodriguez-Sanchez et al., 2014).

3.2. Summary of content analysis on mobile applications

3.2.1. Description of the apps

The characteristics of the 45 relevant apps are summarized in Table 7. In total, we found 15 assistive navigation apps designed for people with mobility impairment, 25 assistive apps for people with hearing impairment, one assistive app for people with cognitive impairment, and 7 assistive apps for older adults from the iOS Apple store and Google play store. The navigation apps were mainly designed for finding accessible places or guiding people with physical impairments to avoid obstacles, architectural barriers, or inaccessible routes. The hearing disabled assistive apps were designed for improving the communication capability for this group of people by analyzing and processing the surrounding sound. People with hearing impairment can hear the world around them better with amplified sound, can receive the real-time information effectively by reading the text translated from the spoken language, or can convert the sign languages into speech and text with the help of those apps. The applications of the seven assistive apps for older adults were more diversified. While three of them were designed for helping older adults to establish a daily exercise route, one supported older adults who are living on their own by providing timely alerts to their family members if a safety issue is suspected, and one was designed for aiding people age 75 years and older considering cardiac catheterization as treatment for a heart attack. Also, the navigation apps for older adults were designed to be simple and allowed them to enlarge the text in the setting.

Thirty-one (31) out of the 45 apps have been updated within one year. Twenty (20) apps were rated four stars or above, the average rating across the 29 apps (with valid ratings) was 3.9. In total, the 45 apps had 9,530 reviews in the Apple App store or Google play store. Specifically, "Hear Boost: Enhanced Recorder" received the most reviews of 4753. Due to the unbalanced number of reviews among the apps and limited access to view full reviews, we were not able to retrieve information by performing a content analysis with user reviews in this study. However, we do believe this can be a future direction if we can gain more access to those reviews. Among the 45 apps, there were 24 apps supported more than one language. Specifically, "Rogervoice" with 80 languages, "SpeakLiz: for deaf people" with 33 languages, and "CaptionMate" with 25 languages were the three apps that supported the most number of languages.

3.2.2. Content analysis of the apps

The design features included in the selective assistive apps for each type of disability are summarized in Table 8. For each disability category, we also counted the frequency (n) and percentage presence (%) of each feature.

3.2.2.1. Hearing impairment. Almost half of the apps (11/25) in this category included the sound recognition system that can convert voice (human voices, music, animals, vehicles) into text, thus the hearing-impaired people can "hear" what is going on by reading the converted text. Also, the system can generate a voice from text inputted by the user, which will help the people without any hearing impairment better "hear" the user with hearing impairment. This voice-to-text and text-to-voice design help improve the efficiency of the information exchange between the users. Less than half the selected apps (8/25) in this category allow the

Table 7. A summary of assistive apps' characteristics.

Name	Developer	Version	Last update	App rating	Number of reviews	Number of supported languages	Target Groups	Application
SpeakLiz: for deaf people	Talov Inc.	4	April, 2021	3	2	33	Hearing impairment	Communication
Transcribe Voice	Kyo Chin	2.0	Mar, 2021	–	0	5	Hearing impairment	Lifestyle
Ava: Best Live Transcription	Transcense Inc.	2.2.6	Mar, 2021	4.3	454	6	Hearing impairment	Communication
Hear Boost: Enhanced Recorder	Future Moments	1.6	Jan, 2021	4	4,753	12	Hearing impairment	Communication
Rogervoice	Rogervoice	4.21.9	Apr, 2022	3.4	1233	80	Hearing impairment	Communication
Listening device, hearing aid	Alecander Bredikhin	2.0.4	Jan, 2021	4.2	297	19	Hearing impairment	Medical
Petralex Hearing Aid App	IT ForYou	2.14.2	Mar, 2021	4.2	958	19	Hearing impairment	Medical
Easy to hear: hearing aid app	IT ForYou	1.6.10	Mar, 2021	4.7	63	2	Hearing impairment	Utilities
BSL education	nuom	1.0.4–speedy	Jun, 2021	2	20	1	Hearing impairment	Education and training
Sign Language for Beginners Guide	Luminous Lunar	1.0.4	Jan, 2021	3.3	27	1	Hearing impairment	Education and training
Sign Language For Beginners	Aesthetic Apps	1.3	Oct, 2020	2.9	476	1	Hearing impairment	Education and training
Cycle Safely	Cyclebell.co.uk	2.0	Nov, 2021	–	0	1	Hearing impairment	travel safety
Hearing amplifier, hearing aid	HEARING AID. LTD	1.0.5	May, 2020	4.6	57	19	Hearing impairment	Medical
CaptionMate	Clarity Products	2.4.1	Feb, 2021	4.6	14	25	Hearing impairment	Lifestyle
TD NEWZ—TREND AND DAILY NEWZ	AHMED KAZEKA	1.5	Mar,2021	–	0	1	Hearing and visual impairment	News and Magazine
Earfy live subtitles/captions	Earfy NV	1.2.3	June, 2019	2.0	4	3	Hearing impairment	Health & Fitness
Visualfy	Visualfy	5.19.1	Mar, 2021	–	0	2	Hearing impairment	Utilities
MAVIS App	Land Transport Authority and SG	2.6.0	May, 2021	1	2	1	Hearing, visual, and mobility impairment	Navigation
Feira Museus	Realizasom	1.0.1	Mar, 2021	–	0	2	Hearing and visual impairment	Navigation
Walk Viseu	Realizasom	1.2.0	May, 2021	–	0	4	Hearing and visual impairment	Navigation
Albufeira Municipal Museum of Archaeology	Realizasom	1.1.1	Jul, 2020	–	0	5	Hearing and visual impairment	Tourism
VGuide SMA	Sharjah Museums	1.0	Apr, 2022	–	0	2	Hearing impairment	Tourism
MNAz—Museu do Azulejo	Realizasom	3.0.0	May, 2021	4.5	4	2	Hearing and visual impairment	Tourism
Costume Museum	Realizasom	1.1	Sep, 2021	–	0	4	Hearing and visual impairment	Tourism
Streetco	Artil	1.9.3	April, 2021	4.1	59	1	Mobility impairment	Navigation
Roll Mobility	Roll App Inc	2.0.3	Feb, 2021	5	3	1	Mobility impairment	Navigation
iAccess Life—Accessibility	iAccess Innovations	2.2	Dec, 2020	4.7	53	1	Mobility impairment	Navigation
WheelMate	Coloplast	1.0.7	April, 2020	4.3	7	5	Mobility impairment	Navigation
WheelMap	Sozialhelden	5.1.0	April, 2020	2.6	6	2	Mobility impairment	Navigation
AccessNow	Accessibility Now	1.60.0	Mar, 2021	4.6	5	1	Mobility impairment	Navigation
Route4U	Route4U	1.8.5	Dec, 2019	–	0	1	Mobility impairment	Navigation
AccessAble	DisabledGo	2.1.9	Mar, 2021	–	0	1	Mobility impairment	Navigation
Ginto	AccessibilityGuide	2.3.8.1690	Sep, 2021	5	1	1	Mobility impairment	Navigation
Scotland Transport: Wheelchair, Maps, Routeplanner (Early Access)	Smart Cities Transport, Sydney NSW, Route Planners	Varies with device	Jun, 2021	–	0	1	Mobility impairment	Navigation
Waverley Transport: Maps, Timetable, Route Planner (Early Access)	Smart Cities Transport, Sydney NSW, Route Planners	2020–08–15 23	Aug, 2020	–	0	1	Mobility impairment	Navigation
Accessible Jordan	dot.jo Co.	1.2.0	Jan, 2022	–	0	2	Mobility impairment and older adults	Navigation
Pokeguide Transportation App	Pokeguide Limited	3.0.14	Mar, 2022	4.9	999	1	Mobility and visual impairment	Navigation
BillionAbles	Billion Ables Services Pvt Ltd	2.3	May, 2020	4.7	10	1	Mobility, hearing, and visual impairment	Navigation
Dooinwell-for older adults	Dooinwell	1.0.9	April, 2021	–	0	4	Older adults	Safer independent living

(continued)

Table 7. Continued.

Name	Developer	Version	Last update	App rating	Number of reviews	Number of supported languages	Target Groups	Application
Exercise for Older Adults	Samantha Roobol	1.2	Nov, 2020	1	3	1	Older adults	Health & Fitness
Workout for Over 50 s	Fitric	1.1	April, 2021	–	0	1	Older adults	Health & Fitness
Leg Exercise for Seniors	vi Nguyen	1.1	Oct,2020	5	1	22	Older adults	Health & Fitness
NSTEMI Decide	Anna S. Kiefer	1.2	Jan, 2021	5	7	2	Older adults	Medical decision aid tool
Presence Caregiver Research	People Power Company	3.1.13	Apr, 2020	4.4	10	1	Older adult	Lifestyle
MemClock	Life's Simple Solutions, LLC	1.3	Jul, 2016	5	2	1	Cognitive impairment	Lifestyle

*Note that the "–" under "App rating" category indicates that the app has not yet received enough ratings or reviews to display a Ratings & Reviews summary in the store.

user to adjust the volume and speed of the voice. Specifically, the two apps "Transcribe Voice" and "Earfy live subtitles/captions" support the flip of the text, thus, the user can present the written note to other people without the need of rotating the phone screen. Since people with hearing impairment mainly rely on observing the screen to obtain information, a few apps (6/25) use large font sizes and icons and allow the users to adjust the font size, font color, and background color to improve the readability of the apps based on their needs. Four apps could identify the sign language of the users and convert them to speech and text to deliver information to people who do not understand it. Specifically, "Visualfy" can allow the user to communicate with the customer care service using the sign language. Furthermore, "Visualfy" can recognize the surrounding sounds such as fire alarms, doorbell, alarm clock, and baby crying, then turn them into visual (color) or sensory (vibration) alerts. Some of the apps (5/25) were able to enhance the voice filter in a noisy environment, which could improve the hearing capability of people with hearing impairment for certain conversations and sounds. In addition, some apps (5/25) provided sign language for education/informational videos.

3.2.2.2. Mobility impairment. Some apps (6/15) ask the user to create their profiles at the very beginning of using the apps. Thus, the system can better search for accessible places or calculate the accessible routes that fit the user's wheelchair size or physical conditions. Most of the apps (9/15) support the nearby searches or category searches of accessible places for the users. A few apps (5/15) allow the user to mark their favorite places, and enable the user to revisit both the favorites and history lists. Six apps can retrieve the results of searched places and allow the user to preview relevant information regarding the places, such as the address, phone numbers, hours of operation, and the accessibility information of places. During the navigation process, some apps can provide the real-time estimated arrival time, distance, and other travel information to the users, and there were two apps that use audio instructions to notify the user. Four of the apps support real-time reporting of obstacles and architectural barriers. Six of the apps allow the user to leave reviews and ratings for accessible places regarding the overall access and bathroom access. Four apps offer the ability to share the user's location, which may be helpful if the user needs to contact someone for help. Only one app (Streetco) enables the user to interact with the system through voice commands.

3.2.2.3. Older adults. Within the seven assistive apps designed for older adults, four used large sizes of visual elements (e.g., fonts, icons) and high color contrast to improve the readability of the contents in the apps. More than half of the apps (4/7) of the apps include the calendar view of activates and reminders that allow the older adults to better manage their to-do lists. Only one app (Dooinwell-for older adults) that is designed to support the older adult to live independently and safely has enabled the location tracking

Table 8. Design features included in assistive apps for people with different types of disabilities.

Design features	Prevalence of features in apps *n* (%)
I. Hearing impairment (Based on 25 reviewed apps)	
Convert voice-to-text and text-to-voice in real-time	11 (44)
Provide adjustable speed & volume of voice	8 (32)
Use of large font and icon size	6 (24)
Provide adjustable font and background color	10 (40)
Recognize sign language	4 (16)
Filter noise and increase the volume of the audio output	5 (20)
Recognize sounds (e.g., fire alarm, doorbell) and alert the users	1 (4)
Provide Sign language for educational/informational videos	5 (20)
Provide subtitles for videos	1 (4)
Provide captions for incoming and live calls/ transcribe voicemails	1 (4)
Provide notifications (e.g., vibration) when a pedestrian or cyclist is approaching	1 (4)
II. Mobility impairment (Based on 15 reviewed apps)	
Allow pre-setting of user profile, e.g., use manual/electric wheelchair	6 (40)
Allow for nearby searches of accessible places around the user	9 (60)
Allow for category searches	5 (33)
Provide favorite and history list	5 (33)
Calculate accessible routes, e.g., wheelchair route	7 (46)
Provide estimated arrival time and distance of travel	5 (33)
Support audio instructions and guidance	2 (13)
Support real-time reports, e.g., obstacles and architectural barriers	4 (26)
Provide detailed information for each place, e.g., address, phone	6 (40)
Leave review and rating for accessible places, e.g., rate bathroom access	6 (40)
Allow for sharing of locations	4 (26)
Allow voice commands, can speak to app	1 (6)
Provide information regarding accessibility of different areas within a building	3 (45)
III. Older adults (Based on 7 reviewed apps)	
Use of large text and icon	4 (57)
Use of high color contrast	5 (71)
Coordinate calendar, set reminders, manage to-do list	4 (57)
Use of older adults' pictures as cover picture	2 (28)
Enable GPS and location tracking	1 (14)
Provide updates and alerts for the family	1 (14)
Provide customizable voice command shortcut	1 (14)
Set emergency contacts and being able to call them	1 (14)
Notify emergency contacts automatically in case of emergencies	1 (14)
IV. Cognitive impairment (Based on one reviewed app)	
Provide reminders with specific actions, timing, and images	1 (100)

feature of users and family alerting feature. Also, the Dooinwell-for older adults is the only app that can get the voice input of older users to interact with the system.

3.2.2.4. Cognitive impairment. Only one app (i.e., MemClock) was found to help people with cognitive impairment. This app provides reminders to the users with specific actions, timing, and images (e.g., a message that says "it is 10 am in the morning, you need to eat your breakfast" with an image of sunrise).

3.2.3. Design guidelines generated from apps' review

Based on the content analysis of the 45 assistive apps, we have identified 10 additional design guidelines that have not been covered by the systematic literature review. These design guidelines were listed in Table 9 along with the related Nielsen's principles and the target beneficiary population.

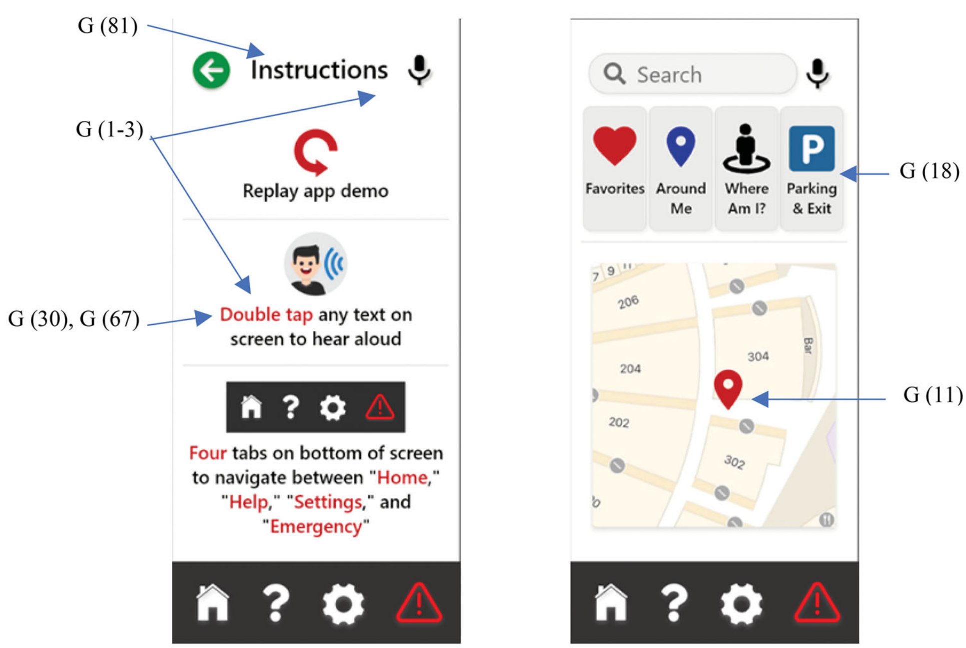
The system should stick to familiar interface conventions based on the users' expectations. One easy way to implement this solution is to allow the users to choose the most comfortable and familiar ways of interacting with the system, which may include the settings of language, distant unit, the preferred route type, color theme, text sizes, speaking rate or pitch, and voice command shortcuts. The transcription between voice and text not only enhances the communication between people, but can also increase the efficiency of information exchange between the users. This feature is especially helpful for people with hearing impairment if the system can recognize sounds such as a fire alarm and timely alert them with visual or tactile cues. In a noisy environment, the users may not be able to hear the audio of the application clearly. Thus, the capability of filtering noise and amplifying weak sounds will help prevent the user from missing important audio information. Allowing the users to create and organize their own list of favorite places can help them to quickly and easily search for a direct route to their favorite traveled places in the future. Similarly, if the system can help record the history list, that will provide the users with easy access to revisit their search record. After the search, the system should allow the user to preview relevant information regarding the places in the retrieved results. For example, by providing the accessibility information and phone number of restaurants, the wheelchair users can better decide which place to pick and can call ahead to confirm the reservation. Except for the accessibility description provided by the accessible places themselves, the user reviews and ratings regarding the overall access, entrance access, and bathroom access will be useful sources to help people with disabilities to evaluate the accessibility of the places. Since older adults or people with cognitive impairment tend to forget things and feel lost more easily, the application should help this group of people to organize and manage

Table 9. The scoping review of apps: Summary of design guidelines.

	Visual	Hearing	Motor	Cognitive	Older adults	Nielsen's Principle
(66) Allow the user to customize system features, e.g., color theme, text size, speaking rate or pitch, and voice command shortcuts.	*	*	*	*	*	Flexibility and efficiency of use
(67) Convert between voice and text in real-time.	*	*	*	*	*	Flexibility and efficiency of use
(68) Notify the users when an emergency or hazardous situation occurs.	*	*	*	*	*	Visibility of system status
(69) Filter and reduce noise & amplify weak sounds.	*	*	*	*	*	Error prevention
(70) Allow the user to revisit favorite and history lists.	*	*	*	*	*	Recognition rather than recall
(71) Provide quick access to some key information of searched place, e.g., address, phone, hours of operation.	*	*	*	*	*	Flexibility and efficiency of use
(72) Allow the user to share their reviews and ratings regard the accessibility of places, e.g., if a place is wheelchair-friendly with accessible entry and restrooms.	*	*	*			Flexibility and efficiency of use
(73) Provide a list of reminders in calendar review to help older adults or people with memory loss better manage their to-do list.				*	*	Recognition rather than recall
(74) Send updates and alerts to the user's family and caregiver.				*	*	Error prevention
(75) Share user's current location/destination	*	*	*	*	*	Help users recognize, diagnose, and recover from errors

Table 10. Additional design guidelines for each type of disabilities.

	Visual	Hearing	Motor	Cognitive	Older adults	Nielsen's Principle
(76) Provide user's real-time location and orientation information.	*	*	*	*	*	Visibility of system status
(77) Give continuous instructions when the app is in background.	*	*	*	*	*	Visibility of system status
(78) Allow cancelation of current interaction.	*	*	*	*	*	User control and freedom
(79) Support reverse route search.	*	*	*	*	*	Flexibility and efficiency of use
(80) Provide instant live help and remote assistance.	*	*	*	*	*	Help and documentation
(81) Include tutorials in the system.	*	*	*	*	*	Help and documentation
(82) Allow the user to provide feedback using "contact us."	*	*	*	*	*	Help and documentation



(a) Tutorial page (b) Home page

Figure 1. Prototype: Part I. (a) Tutorial page. (b) Home page.

(a) Favorite page (b) Around me page (c) Where am I page

(d) Parking garages and exits page (e) Voice-controlled page

Figure 2. Prototype: Part II. (a) Favorite page. (b) Around me page. (c) Where am I page. (d) Parking garages and exits page. (e) Voice-controlled page.

their to-do list in their preferred way and remind them in time, and notify their families or caregivers when detecting any abnormal activities from the users. In addition, with the enabled GPS and location tracking, the system can allow the users to share their current locations and destinations if they get lost.

4. Discussion

4.1. Additional design guidelines

Besides the 75 design guidelines generated from the review of relevant literature and assistive apps, we have identified seven additional guidelines in Table 10 based on our previous study (Zheng et al., 2021). It is recommended that the system convey the real-time location and orientation information of the user so that the users know where they are, whether they are heading to their destination in the right direction. For example, if the real-time location of the users can be displayed in the built-in map, the user will be able to have a sense of proximity within the real world. In addition, the system should allow the user to select if they want to receive the continuous instructions when the app is in the background operations. When the app is running in the background, the user can still receive navigation instructions

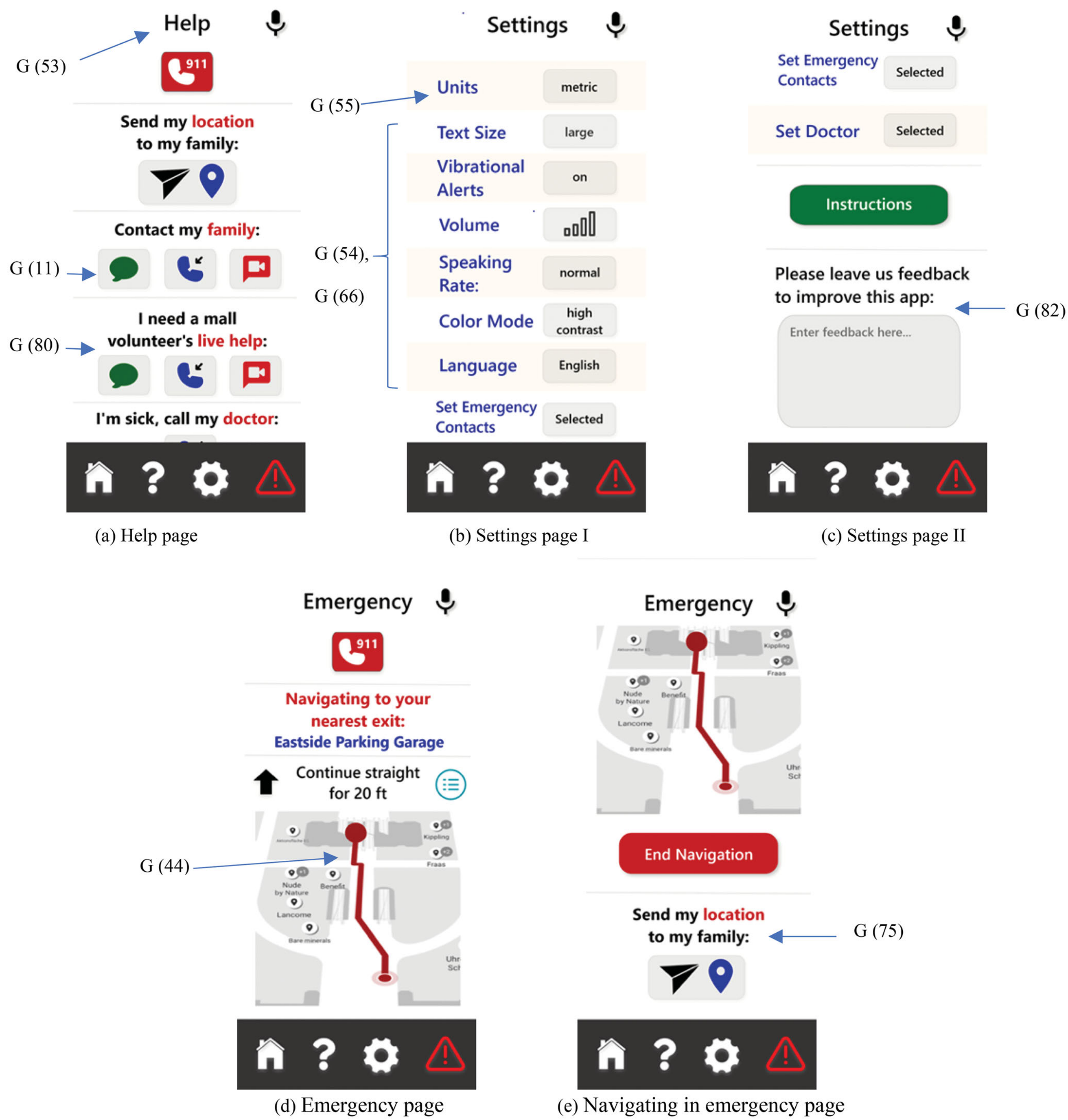


Figure 3. Prototype: Part III. (a) Help page. (b) Settings page I. (c) Settings page II. (d) Emergency page. (e) Navigating in emergency page.

via auditory messages. However, this design guideline might not be appropriate for people with hearing impairment. The system should always display the reverse buttons (e.g., undo, cancel) in an obvious way, thus, the user can easily cancel the action or exit from navigation when performing an unwanted action by mistake. Supporting reverse route search in the application will allow the user to quickly switch between searching of the route from A to B with the route from B to A. Providing instant live help and remote assistance that is easily recognizable and accessible is necessary. Whenever the users need assistance, the system should offer support either via a chatbot or via a human representative based on the characteristics of the user groups. For example, the system should allow individuals with hearing impairment to communicate with the customer care service in sign language. Tutorials in proper modalities should also be provided to give a step-by-step guide on where to start and how to use the application for first-time users. For example, an audio tutorial should be provided to users with low vision. In addition, the help documentation should be easy to search. Finally, the system should include a “contact us” page to allow the user to provide feedback and request features that may help improve the accessibility of the app.

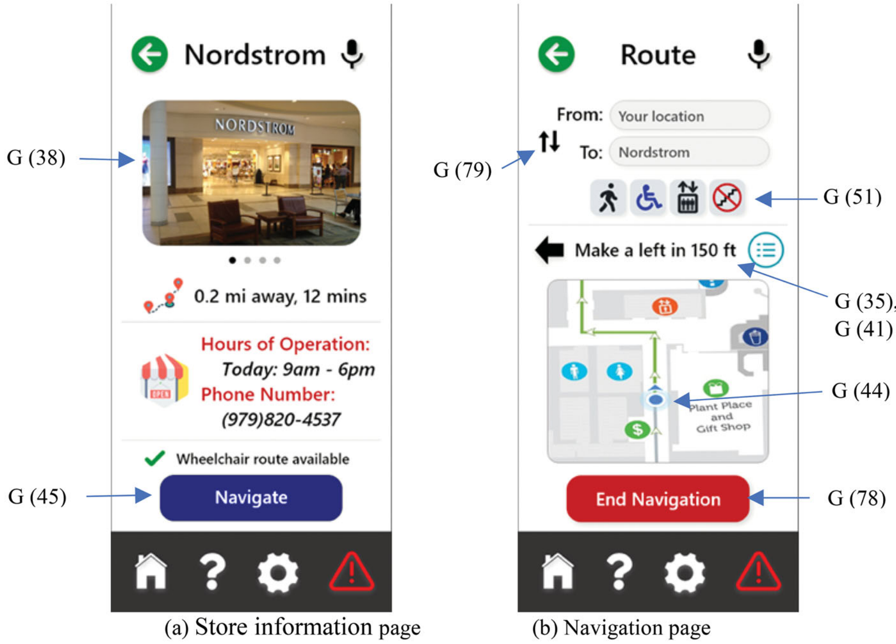


Figure 4. Prototype: Part IV. (a) Store information page. (b) Navigation page.

4.2. Prototype of the navigation system

To demonstrate how the generated guidelines can be implemented, we designed a prototype of a universal indoor navigating app for a shopping mall with Adobe XD. Wayfinding is still a challenge in many indoor environments, especially those that are geographically large, such as shopping malls. The implemented design guidelines have been listed for each application scenario using numbers (1) – (82) from Tables 6, 9, and 10.

4.2.1. Implementation of design guidelines regarding information presentation modality, visually-based interface design, and tactile-based interface design

Figure 1 illustrates the app tutorial and home pages. The numbers in parenthesis (e.g., G (1)) indicate how the specific guidelines from Tables 6, 9, and 10 were implemented in the prototype. The user can use the app to navigate to places within the shopping mall. When the app is opened for the first time, a tutorial will be displayed to guide the user on how to use the app (see Figure 1(a)). After the tutorial is complete, the user will be on the home screen (see Figure 1(b)) where they will have the option to search for a specific destination or choose from four big buttons (i.e., favorites, around me, where am I, and parking & exit).

4.2.2. Implementation of design guidelines regarding information presentation modality, visually-based interface design, information display and communication, and other considerations

Figure 2 illustrates some of the specific functionalities of the app including the "faviorates," "around me," "where am I," "list of parking garages," and "voice-controlled" pages. The "favorites" button will display a screen with a list of all the locations the user has favorited/saved in the past. This list will also display images of the locations to help the user easily recognize the place (see Figure 2(a)). The "around me" button will show different categories of the types of places around the user to help them easily choose where they want to go (see Figure 2(b)). This feature is especially useful for older adults and those with cognitive disabilities as it will simplify the process of choosing a destination. The "where am I" button displays a map and address showing the user's current location and help them scan their environment to see what is around them (see Figure 2(c)) (Lewis et al., 2015). It also provides a written and verbal description of their surroundings. The "parking & exit" button provides a list of the nearby parking garages and exits for the user to navigate to (see Figure 2(d)). All the app screens have a microphone icon in the upper right corner. This is the voice-controlled menu that can be used by pressing the icon and speaking to the phone (see Figure 2(e)). The voice-controlled menu provides a few examples of phrases that can be used. This feature is helpful for visually impaired and cognitively impaired people, as well as older adults.

4.2.3. Implementation of design guidelines regarding visually-based interface design, information display and communication, and preference and support

Figure 3 illustrates the app's four tabs (Home, Help, Settings, and Emergency) at the bottom of the screen. The functionalities of the "home" screen have been described previously. The "Help" screen offers five options of contact for the user to choose from. They can call 911, send their location to their family, contact their family, contact the mall volunteers for live help, or contact their doctor (see Figure 3(a)). For contacting their family and mall volunteers, they have the options of text message, phone call, or video chat. The Settings screen has various options that can be customized to the user's preferences. Some of these include units, text size, vibrational alerts, volume, speaking rate, color mode, and language (see Figure 3(b)). There is also an option to leave feedback for the app developers (see Figure 3(c)). Additionally, the "instructions" button on this screen will allow the user to replay the tutorial and read/hear step-by-step instructions on how to use the app. The Emergency screen begins navigating the user to the nearest exit in the case of an emergency where they need to evacuate the building immediately (see Figure 3(d, e)). It also includes the option to call 911 and send their location to their family members.

4.2.4. Implementation of design guidelines regarding information display and communication and adaptation to user's needs

Figure 4 provides more information on the navigation capability of the prototype. When the user selects a destination, a screen with the destination's photo, the distance of travel, hours of operation, phone number, and wheelchair route availability is displayed (see Figure 4(a)). Then the user can choose to navigate to that location. The navigation routes offer four options (walking, wheelchair, elevator, and no stairs) (see Figure 4(b)). This allows the user to choose the route which is most suitable for their needs.

4.2.4. Implementation of design guidelines regarding information presentation modality and tactile-based interface design

Some features of the app that are not shown in the screens themselves are the audio/vibrational capabilities. All the text in the app can be read aloud if double tapped. This is useful for individuals with visual or cognitive impairments. There are also auditory and vibrational alerts in the case of an emergency to alert the user. Vibrational alerts are also used during navigation to guide the user along the path and notify them of any upcoming landmarks. These vibrational alerts are helpful for visually and hearing-impaired individuals since it easily notifies them of the status of their surroundings.

5. Conclusions

The objective of this work was to formulate a set of design guidelines that can be used to improve the accessibility of navigation apps for people with various types of disabilities. We developed a list of design guidelines based on the insights gained from reviewing the literature and qualitatively analyzing the relevant apps. In total, 82 design guidelines were proposed and categorized based on Nielsen's usability principles. To validate and demonstrate how the design guidelines can be applied to design the navigation system, we developed an interface prototype to assist the user to navigate places within a shopping mall. The prototype has demonstrated that the proposed design guidelines are easily applicable and provided a roadmap for the future design of navigation apps for people with different types of disabilities.

This study had some limitations that need to be addressed in future research. The current version of design guidelines is generated from the literature review and app analysis. To validate and refine the set of design guidelines, we conducted a heuristic evaluation study with five usability experts (Shahini et al., Under review) and are currently conducting user testing with individuals with visual, cognitive, hearing, or mobility impairment and older adults. The findings of heuristic evaluation and user testing with 28 human participants with disabilities suggested that all users could complete the tasks (e.g., find the nearest bathroom or emergency exit) and found the interface to be useful for indoor navigation. They provided specific comments on how to improve the visibility and consistency of the interface and prevent errors. Another limitation is that the proposed guidelines were focused on designing navigation apps for people with disabilities. However, combining different functionalities in one app (e.g., navigation, workout, etc.) might be beneficial and need to be explored in future research.

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